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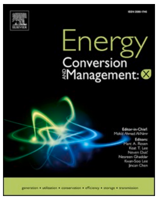

Conceptualization of a vehicle-to-grid assisted nation-wide renewable energy system – A case study with spain

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ABSTRACT

This study explores the potential of Vehicle-to-Grid (V2G) technology in utilizing Electric Vehicle (EV) batteries for energy storage, aiming to fulfil Spain's 2030 and 2050 energy goals. The validated Simulink model uses 3.15 million EVs in 2030 and 22.7 million EVs in 2050 as primary energy storage. The results show that Spain can achieve its 2030 target of 42 % renewable energy by utilizing 800 GW of PV + Wind, or 220 GW of installations combined with an annual import of 18 TWh. For the 2050 goal of 97 % renewable energy, the study proposes 1300 GW installation without external support, or 600 GW renewable energy source installation with a 50 TWh import. Detailed analysis shows that the storage provided by 3.15 million EVs can replace 122 GW of new energy storage installation in 2030 and 22.7 million EVs replace 2.7 TW of new energy storage requirements in 2050 to support high penetration of intermittent renewable energy installations. The analysis showcases the substantial storage capacity provided by EVs, emphasizing their potential as a primary ESS and the effectiveness of V2G technology in grid support. The overall results underscore V2G technology's role in minimizing the need for additional energy storage infrastructure in the future.

1. Introduction

Renewable energy offers the most promising solution to generating green electricity. Renewable energy (RE) sources include photovoltaics (PV), wind energy, geothermal energy, hydropower plants, and bio-energy fuels. Besides being sustainable, renewable energy systems (RES) have other advantages, such as local availability and reducing the dependence on imported energy. From a grid standpoint, the inclusion of high-penetration distributed RES helps to improve the voltage profile, better energy scheduling and reduced energy cost [1]. The European Union (EU) targets reducing greenhouse gases by 55 % in 2030 (compared to 1990 levels) and aims to become a climate-neutral continent by 2050 [2]. For meeting these low greenhouse gas emission demands, the combination of variable RES, such as PV and wind, and energy storage systems (ESS) is essential. The EU aims to achieve 100 % carbon neutral and 100 % renewable electricity (RElec) generation in EU nations by 2050 [3].

Several studies support the concept of a 100 % RES for zero-emissions goals. The International Renewable Energy Agency (IRENA) report shows the global mapping of 100 % renewable energy targets and puts together several case studies from national, regional, city and island levels to illustrate different paths to a 100 % RE transformation [4]. The report shows that a 100 % RE system is achievable, but each country requires tailor-made frameworks to include local circumstances. The International Energy Agency (IEA) study on the global net zero emission pathway shows that the global energy demand will go down by 8 % in 2050 [5]. Their report describes that PV and wind installation need to increase 20-fold and 11-fold, respectively, to meet the demands. In 2021, IEA analysed the possibility of France achieving net zero emission through 100 % RE sources and the results show that improving energy efficiency and scaling up PV and wind installations as key pillars to reaching a 100 % RE system [6].

Various studies have investigated to potential of 100 % RE-systems in different regions. Caglayan et al. [7] investigate the possibility of the European energy supply with 100 % RE sources and show various Nordic countries, Germany and France could be potential energy exporters to the rest of Europe in the long run. A 100 % RE system study in the United States of America by Denholm et al [8] points out economic imbalance and the development of the grid to sustain 100 % RE sources. Through a grid integration model-LOADMATCH, Jacobson et al [9] study shows that 100 % RES is possible with low cost and no-load loss in the USA. Including 1065 GW storage capacity in 2050–2055, the levelized cost of energy (LCOE) would be around ~11.37 ¢/kWh (in 2013

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Nomenclature

$Cap_{T\text{-}EV}$	*Total battery capacity*
$E_{ava\text{-}EV}$	*Energy available in EV*
E_B	*Energy balance*
E_{EV}	*EV energy consumption*
ESIG	*Energy system integration group*
ESS	*Energy storage system*
EU	*European union*
EV	*Electric vehicles*
FEC	*Final energy consumption*
GW	*Giga watt*
GWh	*Giga watt-hour*
HP	*Hydro power system*
HR	*Hourly reliability*
IEA	*International energy agency*
IRENA	*International Renewable Energy Agency*
kW	*Kilo watt*
kWh	*Kilo watt hour*
LCOE	*Levelised Cost of Energy*
m_s	*EV share of moving vehicles*
PHS	*Pumped hydro storage system*
P_s	*EV share of parked vehicles*
PV	*Photovoltaics*
RE	*Renewable energy*
RES	*Renewable energy source*
$S_{ava\text{-}EV}$	*The storage capacity available in EV*
SOC	*State of Charge*
$SOC\_M_{EV(x+1)}$	*Updated SOC of moving vehicles*
$SOC\_P_{EV(x+1)}$	*Updated SOC of parked vehicles*
$SOC_{EV(x+1)}$	*SOC of the EV fleet at the end of the time period*
$SOC_{EV\text{-}x}$	*SOC of the EV fleet at the beginning of the time period*
SS	*Self-sufficiency*
TW	*Tera watt*
TWh	*Tera watt-hour*
V2G	*Vehicle-to-grid technology*

dollars). Studies by the Institute for Sustainable Futures in 2017,2019 and 2020 [10–12] highlight the possibility of a 100 % RE system in Tanzania, Bangladesh and Costa Rica. For Tanzania, 60 GW of combined RE installation is estimated to meet 110 TWh of electricity demand in 2050 [10]. To meet the 380 TWh energy requirements of Bangladesh in 2050, authors estimate 76 % of energy generation from 150 to 200 GW installation of RE sources (56 % of 76 % from wind and solar energy) [11]. For Costa Rica, the study estimates 2.4 GW of hydropower, 4 GW of wind installations and 12.8 GW of solar PV installation to meet the energy demands [12]. The study by Andrew Blaker [13] focuses on analysing 100 % RE in Australia with PHS system reports with 23 GW of Solar PV, 45 GW of wind installation, 7.4 hydropower system, 16 GW of pumped hydro system and 0.6 GW of biomass, the annual demand of 205 TWh can be met. The energy security of Jordan with 100 % RE in 2050 is analysed by Azzuni et al [14]. Using the LUT Energy System Transition model (LUT-ESTM) result shows that to meet the primary energy demand of 130 TWh in 2050, 25 GW of solar PV, 11 GW of concentrated solar power, 5 GW of wind power and 90 GWh of storage capacity is required. With 92 % of total energy generation from solar PV, their study also shows that the LCOE drops from 78 €/MWh in 2015 to 61 €/MWh in 2050. Furthermore, the 100 % RE system in Europe is also analysed with the LUT-ESTM model [15]. The results show that a total energy installation of 3100 GW is needed with 62 % PV, 17 % wind, 7 % hydropower and the rest from other sources. Using the same LUT-ESTM model, a few other studies analyse the possibility of a 100 % RES system for Finland and the Åland Islands [1617]. Several studies conducted in other parts of the world also show that shifting to 100 % RES over the next 20 years is possible and that energy costs would become lower than before [1819–212223].

Apart from nationwide studies, localised studies were also done for various cities. The possibility of converting the municipality of Aalborg to a 100 % smart energy community is done by Thellufsen et al [24]. Through Energyplan software, the results from the study show that wind will be the primary energy generation unit generating 43 % of total energy demand, followed by biomass/waste with 32 % of energy generation and PV with 10 % of energy generation. The study by Lu et al [25] examines the 90–100 % RE system for Western Australia. The result shows additional 20–30 % of RES installation is needed to generate 100 % RElec with higher LCOE ($129/MWh) compared to 90 % RElec system ($117/MWh). The report by the Energy Systems Integration Group (ESIG) on “Towards 100 % renewable energy pathways” concludes that a 100 % RE system with right balance between reliability and cost is the most optimal rather than achieving at a high cost and/or a low level of reliability [26].

From all the studies above, we can identify the energy storage system (ESS) as an integral part of 100 % RES. Apart from countries that have hydropower in abundant, solar PV or wind would be the primary RE source. The unpredictable nature of PV and wind energy generation demands a large ESS capacity [27]. Considering thermal energy storage, hydro storage, and mechanical and electrochemical storage, IRENA estimates the need to triple the ESS to meet the growing demands [28]. At the end of 2020, the world’s total installed energy storage capacity was 34 GWh and expect to reach 1 TWh by 2030 [29]. The US Department of Energy’s global energy storage database reports that, as of 2020, PHS accounts for 95 % of the current world storage capacity [30]. With a high round-trip efficiency and low response time, pumped hydro energy storage systems (PHS) were previously considered the best energy storage solution [31,32]. Nevertheless, The US Department of Energy estimates that battery technology will be the most dominant form of energy storage shortly due to the rapid increase of electric vehicles (EVs). They estimate a growth factor of 3–5 times in the next ten years, reaching a storage capacity of 2.5——4 TWh in 2030 [30]. To reach 100 % RES; for Jordan, 90 GWh of energy storage is estimated [14], and 1065 GWh of energy storage is projected for the USA to reach 100 % low-cost RE penetration [9]. For Western Australia, 1.5 GW of pumped hydro for 10 h is estimated to meet 100 % RElec in Western Australia [25]. To meet the former ESS capacity, it is required to build a new ESS. This requires more raw materials and financial and economic resources. Given limited resources, it is critical to utilise already existing energy storage possibilities, such as the vast aggregated battery capacity that can offer by the large electric vehicle (EV) fleets. Considering the levelized cost of storage (LCOS) of $480/MWh for pumped hydro, $560/MWh for flywheel, $280/MWh for lithium-ion ESS, $210/MWh for vanadium redox flow, $158–290/MWh for V2G technology in a colder climate and $200–250/MWh for hydrogens storage, energy storage V2G seems cheaper and favourable [33–35].

In this study, instead of traditional ESS, we focus on vehicle-to-grid technology (V2G) to achieve high penetration of RES. Various studies have shown interest in (V2G) from 2017 as a viable ESS to store excess energy in electric vehicle (EV) batteries. Being stationary 95 % of the time, EVs could become an essential part of our energy systems [36]. Boström et al. [37] analyse a pure PV-EV energy system PV as the only electricity source working solely with EVs to satisfy the nationwide energy requirement in Spain. Their result showed that an hourly reliability of 100 % is possible with 73 m^2 of PV per capita in Spain, solely using EVs for energy storage and balancing. Sagaria et al [38] show that

Table 1
Characteristics of V2G studies focusing on regional/nationwide deployment.

Study	EV fleet size	High VRE share	Varied grid mix	EV storage interaction	Social and technical variable interaction	Energy exchange interaction
[37]	29.4 M			x		
[38]	15 M	x		x		
[39]	0.2 M	x		x		
[42]				x	x	
[50]	4 M	x	x			
[51]	1 M			x	x	
[52]	14.7 M	x		x		
[53]	9 M	X	x	x		
This study	0 – 28.7 M	x	x	x	x	x

Germany can achieve its 2035 energy goals to generate and supply 80 % Renewable electricity through EV as ESS. Sassi et al. [39] analyse the suitability of V2G technology to meet the Moroccan national grid. Their study shows that shifting to EV and accommodating V2G will provide 7.7 GW of controllable energy storage in 2030. The studies [4041–4440] examine the peak load shaving capacity, techno-economic analysis and grid parameters using V2G technology. The results show that the power demand can reduce by up to 6 % with a proper energy management system. Further, advanced energy concepts on energy generation in EVs through onboard PV can also supply energy back to the grid to support the energy system [45].

Schuller et al. [46] developed an optimization model aimed at maximizing the utilization of Electric Vehicles (EVs) and Variable Renewable Energy (VRE) under various power generation and charging infrastructure scenarios. Their findings highlight the potential of coordinated charging, which could more than double VRE utilization, although the effectiveness is constrained by the length of the lookahead period. Mehrjerdi and Rakhshani [47] utilized stochastic programming to optimize the charging and discharging of EVs in a 33-bus distribution grid. The objective was to mitigate VRE intermittency and reduce battery cycling. Nezamoddini and Wang [48] approached the challenge from the perspective of ISOs, incorporating uncertainties in VRE output, load and parking patterns, and transmission line reliability to optimize Vehicle-to-Grid (V2G) dispatch. However, the limitation across these studies is the relatively smaller vehicle fleets and system size. Consequently, the results of larger power systems, where extensive EV fleets and long-term VRE investment decisions, remain uncertain. In a recent study by Zhao et al [49], the environmental impacts of Vehicle-to-Grid (V2G) technology were evaluated within the context of a 2050 United Kingdom system, employing a consequential Life Cycle Assessment (LCA) methodology. The results show that implementation of V2G has the potential to effectively offset the environmental footprint of electricity generation in high RE scenarios, however, the model neglects time-dependent dispatch and other system dynamics. Table 1 presents additional research on the regional or nationwide deployment of V2G dispatch, along with the specific characteristics from the studies.

After Examining numerous previous research works, we can observe that several delve into V2G research, as discussed earlier. However, these studies primarily concentrate on energy systems with high penetration of renewable energy systems with a limited energy mix. Moreover, there is a lack of emphasis on the social and technical variables interaction within the developed model. Additionally, a significant portion of the studies do not consider the possibilities of energy exchange with other nations to enable 100 % RE systems.

In contrast to the studies, our research exclusively centres on V2G technology, considering varying EV volumes, high penetration of RES with a diverse grid mix, energy exchange possibilities, and interactions among social and technical variables.

The main contribution of the paper is to shed light on the potential of V2G technology to support a nation with high penetration of renewable energy sources. By demonstrating the capability of interconnecting stand-alone EVs into a virtual ESS, the paper emphasizes the role of V2G in enhancing grid stability, balancing energy demand, and reducing the reliance on traditional energy storage solutions. The multi-variable simulation model provides high parameter flexibility in considering EV parameters for V2G simulations. Through sensitivity analyses, the paper identifies critical factors influencing the model, such as EV volume, V2G acceptance, battery availability and energy exchange between nations. This allows us to identify key dependencies of the model, offering insights into the feasibility of achieving energy goals under various scenarios. Recognising these factors improves the understanding of the potential challenges and opportunities associated with different configurations of the energy system, ultimately contributing to more informed decision-making, crucial for policymakers, researchers, and industry stakeholders in developing strategies to encourage V2G adoption.

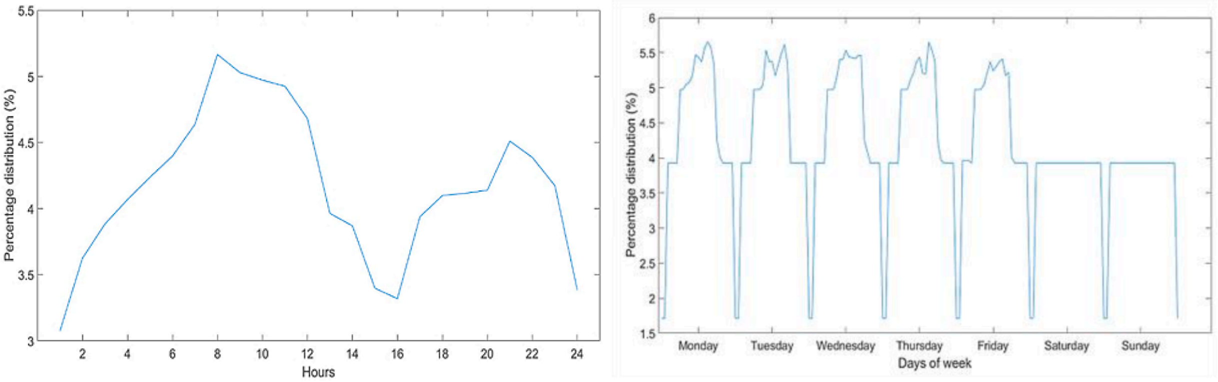
Considering the currently available ESS as secondary storage options, the study examines the feasibility of electrifying a nation depending exclusively on V2G for energy storage. For this analysis, we chose Spain because of its high penetration RE goals in 2030 and 2050, renewable energy and energy storage system growth plans. With 47 % RElec generation in 2021, 40 % RElec is from wind, 10 % from solar and the rest from hydropower and other sources [54]. In 2050, Spain aims to have 100 % RElec and 97 % of total energy from RE sources [55]. This study progresses through the simulation analysis. We develop the model in MATLAB/Simulink interface. With PV, wind and hydropower as RES, the model considers V2G for primary energy storage and pumped hydro system as secondary ESS. The main objectives of this study are to:

- Identify the potential of V2G technology as a future ESS.
- Estimate RES installations (PV and wind) required to meet Spain's 2030 and 2050 energy goals.
- Estimate the number of EVs requires compared to secondary ESS to meet the energy goals through V2G technology.

The remainder of this paper is organised as follows. Section 2 describes i) the modelling principle and methods and ii) the different operational conditions in which the model is tested. Section 3 gives the results obtained by the simulation model under various operational scenarios. Section 4 comprises a discussion of the results and assumptions made, and Section 5 presents the conclusion of this study.

2. Modelling and method

This research aims to study the self-sufficiency of RES systems with EV as ESS to meet grid load requirements. The use of RES and EVs is being studied to achieve this. We develop a simulation model to perform the study in MATLAB/Simulink. In this case study, Spain is the focus country. Using the total electricity consumption (section 2.1), we calculate the hourly electricity consumption for the household and industrial, sectors. We use hourly data from RES as input for the simulation (sections 2.2, 2.3 and 2.4). Section 2.5 also explains the EV's stationary and moving pattern using a log-normal distribution function during each hour. The model's primary focus is simulating the energy flow between the RES, ESS, and the grid. The pseudo-code (section 2.5) explains how the model works. The different operation scenarios



(a) Hourly household load profile   *(b) weekly load profile for the industrial load*

Fig. 1. (a) Hourly household load profile. (b) weekly load profile for the industrial load.

Table 2
Energy generation distribution between sources.

Energy source	Nature of source	2030 Scenario	2050 Scenario
PV and wind	Non – flexible	42 %	97 %
Hydropower	Flexible		
Other renewable energy sources	Flexible		
Oil	Flexible	25 %	–
Natural gas	Flexible	33 %	3 %

envisioned for this study are discussed in section 2.6.

2.1. Energy demand and load profile

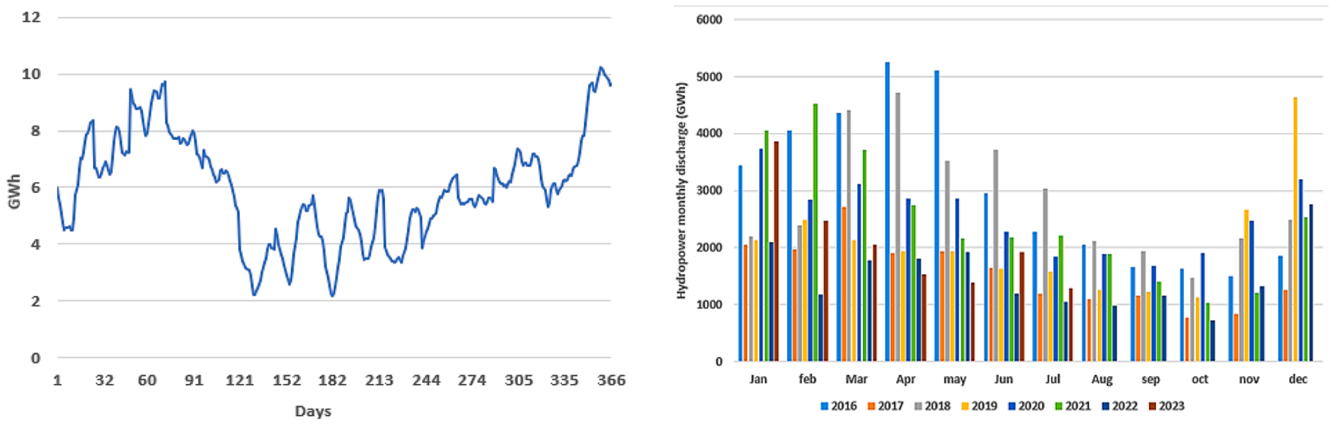
The Annual energy demand of Spain comprises energy consumption in industries, for transportation, for residential purposes, for commercial and public services, for agriculture and other uses. With an average Final annual energy consumption (FEC) of 970 TWh (3496722 TJ) between 2010 and 2020 [56], the transportation sector accounts for 36.3 % of FEC, industry accounts for 23.9 % of FEC, residential usage accounts for 18.3 %, commercial and public usage accounts for 11.5 % and rest of the FEC is used for forestry, fishing and non-energy usages [56]. Since there are no validated load profiles, we generate the load profiles from FEC. By using Sandel et al. 's model [5737], we generated hourly load profiles. Fig. 1 shows the hourly load profile for household energy consumption and the weekly load profile for industrial applications. As the model calculates the energy demand for transportation separately, 36 % of the energy demand by the transportation sector is excluded from the load profile. For the household load profile, we assume constant load demand every day throughout the year. This daily load is then divided into hourly consumption, based on Sandel et al. 's model [57]. Fig. 1a shows the hourly load profile of a household for a day. For the industrial load profile, the model generates a weekly constant load profile with hourly load distribution based on Sandel et al. 's model [57]. The model assumes the same base load throughout the week and a reduced workload during the weekdays. Fig. 1b shows the weekly distribution load profile of industrial sectors.

To analyse the future scenarios, it is required to estimate future electricity consumption. From the FEC data of Spain in the previous years, it can be observed that the FEC each year is declining by 1 % (from 2011 to 2019) [5658]. In addition to this, The study by Sahin [59] found that Spain's gross FEC will reduce by up to 20 % in 2030 compared to the gross FEC in 2005 and less than 2 % compared to the gross FEC in 2018 (Fig. 8 - [59]). The study used an optimised fractional nonlinear grey Bernoulli model to study the electricity consumption of different countries in 2030. As a result, the yearly final energy consumption remains the same throughout the study. However, it is to be noted that the electricity demand rises as more sectors focus on getting electrified. One of the objectives of this study is to estimate the additional RES installation to meet this increasing electricity demand.

This paper mainly focuses on the 2030 energy goal – where 42 % of the annual energy supply is from RES and the 2050 energy goals of Spain – where 97 % energy supply is from RES. For the 2030 scenario, meeting the 42 % energy demand from RES, the rest of the energy is assumed to be from non–renewable energy sources. As of 2020, Oil (42.7 %), Natural gas (22.6 %) and nuclear fuel (10.2 %) are the main non-renewable energy sources followed by coal (2.39 %) [5660]. Progressing towards 2030 energy goals, Spain schedules the decommissioning of coal and nuclear power plants in 2030, while continuing the operation of natural gas combined cycle power plants to supply one-third of the energy demand and oil to supply the rest of the energy need [55]. Focusing on this, for 2030 operation scenarios, the model considers oil and natural gas as non-renewable sources. For the 2050 scenario, the model considers only natural gas as a non-renewable energy source. The energy generation distribution for the above two scenarios in the model is shown in Table 2.

Flexible energy sources represent the ability of the source to increase or decrease the energy supply based on demand. The term Flexibility is related to electric energy and refers to "the extent to which a power system can modify electricity production or consumption in response to variability" [61]. Even though non-renewable energy sources are used for various purposes other than electricity generation at present, in the future, electricity will be used as the primary power source, which will be converted into mechanical and thermal energy [62]. For flexible energy, the model considers flexibility in terms of its average energy supply per hour. With a 33 % annual contribution for the demand of 970 TWh, the model considers the annual output of 320.1 TWh from natural gas with an hourly supply of 58 GW throughout the year. Considering a flexibility of 10 %, the corresponding source can increase the generation by 10 % during the high load demand period and reduce the supply by 10 % during low load demand periods. Normal coal and gas power plants have a minimum load generation of 30 % from the rated power and they can ramp up the production to 100 % if desired [63]. While the new state-of-the-art power plant can reduce the minimum load even further down to 15–20 % [64].

In the model, we give the flexible energy sources a flexibility option of 35 % with an average load generation of 65 % each hour. In high-load demand periods, the energy source can ramp up the production by 35 % more to reach 100 % of the rated power and during low-load demand periods, the energy generation can be brought down by 35 % to 30 % of the rated power. The same flexibility is added to all flexible energy sources, except hydropower systems. Hydropower systems can reduce their minimum load generation by up to 1 % of rated power if desired



(a) Average yearly wind electricity production in Spain (b) *Monthly energy generation from Hydropower from 2016-2022*

Fig. 2. Renewable energy generation data.

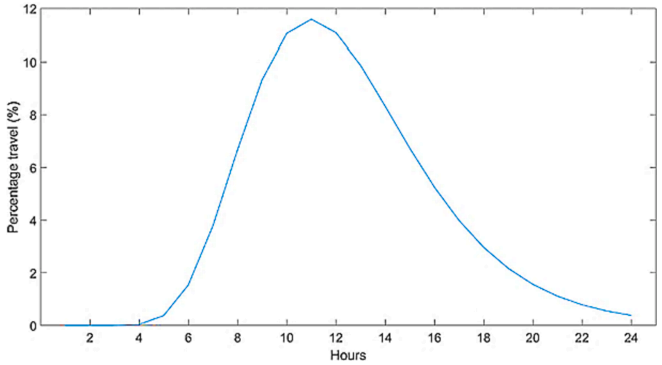


Fig. 3. EV driving distribution for 24 h(1 day) [37].

and can increase the supply to 100 % without any technical difficulties [65]. This makes hydropower the most flexible energy source in this study. Instead of hourly energy supply like other sources, hydropower only operates when the other sources fail to supply the total demand. The operation of hydropower and other RE sources is explained in section 2.2.

2.2. Renewable energy sources (RES)

In this study, we consider PV, Wind, and hydropower (HP) as RE sources. As of 2020, Spain has an installed capacity of 11.5 GW_p of PV with an average annual output of 15.3 TWh energy [66,67]. The energy generation from the PV system is taken from the PV energy generation data - PVGIS database (Photo-Voltaic Geographical Information Systems) [68]. This 15.3 TWh energy generation from 11.5 GW_p of PV gives an annual capacity factor of 15.2 % [66,67]. While in 2019, 8.7 GW_p installation produced 9.2 TWh of electricity, with a capacity factor of 12.2 %. For this study, we assume an average capacity factor of 13.65 % from the former data for PV installation. Along with the capacity factor and hourly yield data from the PVGIS database, the model estimates the hourly PV energy generation for each MW installation.

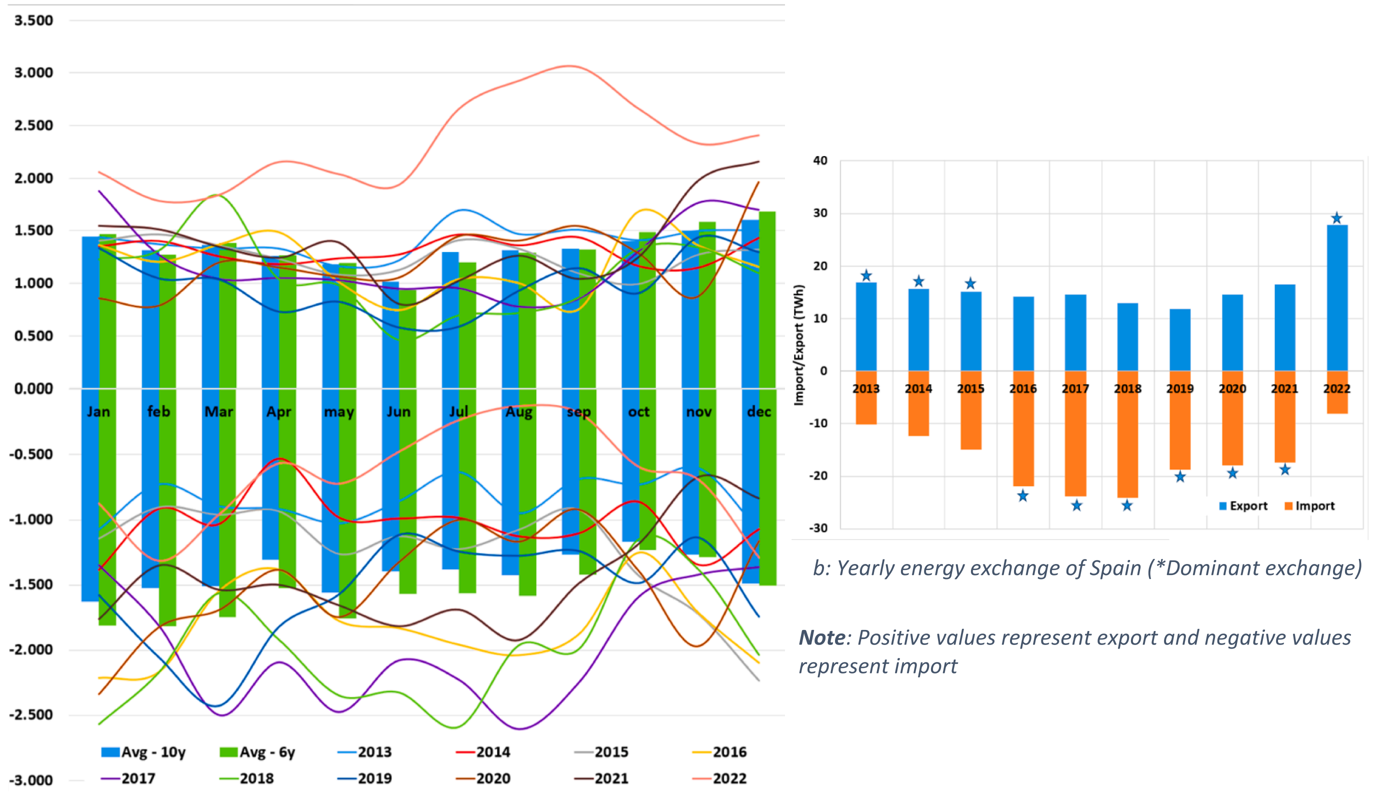
Over the last decade, the growth in wind installation was low in Spain. From 2015 to 2018, the total wind capacity installed increased by just 0,5 GW (from 23.0 GW_p in 2015 to 23.5 GW_p in 2018). The electricity production data during these years shows an average energy production of 47.9 TWh/year. With 47.9 TWh energy generation, the capacity factor falls between 23 and 24 %. Fig. 2a shows the hourly wind electricity production in Spain in 2020, with a capacity factor of 23.6 %. The wind energy production data is collected through the RED Electrica de Espana data depository [69]. Using the energy generation profile from 2020 as a reference, the model estimates the hourly energy generation from wind installations.

The model also includes hydropower (HP) as a RE source. Hydroelectric power, also called hydropower, produces electricity through the kinetic energy of flowing water. This conventional way of electricity production depends upon water stored in reservoirs. With an HP capacity of 20.1 GW between 2015 and 2020; the annual average energy generation of Spain is 28.7 TWh [7071]. Due to uncertainties with the average inflow of water, the net head, and the discharge rate from HP plants across the country, it is challenging to develop a model that estimates the water level in the reservoir of HP each hour. To overcome this challenge, the model includes a more straightforward HP system which considers the annual average output over the past years (28.7 TWh), the average rainfall distribution, the average monthly energy generation from HP in Spain over the years [72] and the rated HP output (20.4 GW [73]). During high-demand periods, the HP discharges energy, whereas the maximum discharge per hour is limited by the rated power and the monthly maximum discharge limit will be the maximum discharge reported in the respective month in the last 6 years (Fig. 2b). This helps to develop an energy generation profile from hydropower without overproduction of energy. In addition to this, the model considers other renewable energy sources such as biomass, waste, and geothermal sources. Supporting RE sources in the future, Spain also aims to improve the contribution from biomass, waste and other RE sources. For other RE sources, the model looks at the mix in yearly contribution and generates a constant output throughout the year to match it.

2.3. Energy storage system (ESS)

The energy storage system (ESS) is a vital component in the energy system to support RE penetration. The model considers two types of ESS for this study, primary ESS, and secondary ESS. When the energy sources fail to fulfil the demand, or there's excess energy from the energy sources, the ESS will engage. The study analyses the performance of V2G as a futuristic ESS. Due to this, the energy storage in EV batteries through V2G is the primary mode of energy storage. To include the presently available energy storage system in a country, we consider existing ESS as secondary ESS that could continue to be utilized in the future. In this case study, the pumped hydro system (PHS) is taken as a secondary energy storage system. As of 2020, PHS is the only energy storage Spain has installed at scale. Having V2G as the primary ESS implies that no new investments will be made on other ESSs.

To facilitate V2G, we consider that the vehicle fleet consists of only private light-duty vehicles. For private light-duty vehicles, the average distance travelled per day combining all vehicle types is 49 km, with an average energy consumption of 220 Wh/km [37]. The log-normal



b: Yearly energy exchange of Spain (*Dominant exchange)

Note: Positive values represent export and negative values represent import

a: monthly energy exchange of Spain [x axis: energy exchange (TWh)]

Fig. 4. Energy exchange of Spain in between 2013 and 2022.

distribution function gives a probability, showing the percentage of vehicles moving each hour The probability distribution function helps to generate the log-normal distribution pattern to characterise the vehicle operation during various hours. Fig. 3 shows the percentage of moving EVs during each hour.

During the energy transfer process, there is a loss of energy. For V2G purposes, the model considers an energy loss of 6.5 % for the charging and discharging process each, with 93.5 % one-way efficiency. Hence, the round-trip efficiency of the V2G technology becomes 87 %. Currently, EVs offer battery packs that vary from 60 kWh to 100 kWh [74]. For this study, the model considers a 100 kWh battery pack for each vehicle [74]. The initial state of charge (SOC) is set at 50 %. Considering the optimal battery life, the recommended maximum SOC that the EV fleet to charge is 80 % and the minimum SOC is 20 % while discharging to avoid extra losses, battery degradation, and improved battery life [75]. In this study, we also consider the whole EV fleet as one big battery system. This leads to having the same SOC for all the EVs in the fleet at any particular time. Finally, we also assume that the nation has a 1:1 EV-to-charger ratio and that all EVs are connected to bi-directional chargers when it is stationary to facilitate V2G energy transfer. At the end of 2020, the total EV registration in Spain was 87,000, which is less than 1 % of the total registered vehicles [76]. With 28.7 million total vehicles registered in 2020, Spain aims to have EVs between 2.7 and 3.6 million vehicles in 2030, and only zero carbon emissions with EVs, fuel cell vehicles and biofuel-powered vehicles in 2050 [777879].

Pumped hydro storage systems (PHS) are energy storage devices to store electricity in the form of potential energy. The system consists of two reservoirs and a turbine/pump. The PHS activates by pumping water from the lower reservoir to a higher reservoir. When electricity is required, water will flow through the turbine to produce electricity. Currently, Spain has a total PHS capacity of 5.54 GW, with 2.75 TWh energy generation in 2020 [8081]. The model also considers a 5.54 GW installed capacity for the futuristic study with a round trip efficiency of 80 % [82]. The model assumes the maximum water levels in the top reservoir are 100 %, and the minimum water level of the reservoir is considered 30 % in the simulations.

2.4. Energy import and export

To improve national energy economies and energy security, energy imports and exports are important. With Spain, most energy exchange is happening with the neighbouring countries Andorra, France, Morocco, and Portugal. Over the last decade, Spain both imported energy from and exported energy to these countries, of which Spain was a net exporter for 4 years and a net importer for 6 years (*Appendix 1*). The highest amount of imported electricity was 24.02 TWh in 2018, while the highest export was 27.83 TWh in 2022. Fig. 4 shows the energy exchange of Spain over the last 10 years.

From the energy exchange data over the last decade, the import and export data are separated into the annual energy exchange, monthly exchange, and average exchange over the period. Fig. 4a shows the energy exchange (import and export) per month over the period, Fig. 4b shows the annual energy exchange over the decade and Fig. 4c shows the distribution of the energy import and export. In the simulation model, we consider energy trade/exchange between countries in certain scenarios. Considering the energy trade for the simulation, the maximum energy import and export possible is given as input. As a result, the model helps to identify the changes in RE installation and ESS installation needs in operational conditions. However, in reality, energy exchange occurs gradually over time and is constrained by the capacity of international connections. Therefore, the system should not permit the use of all imports in a concentrated time frame, like imports during the winter and exports during the summer. The import or export should be distributed over the period. To restrict this, the model follows the average monthly distribution of imports and exports from the past data.

```
Start:  1: Read Inputs:
        2: Estimate energy consumption for EV fleet ($E_{EV}$)
        3: Estimate Energy balance ($E_B$)
        4: Determine energy flow between systems based on $E_B$
           IF $E_B$ is greater than zero; shows higher energy demand than RE generation.
              IF  Energy stored in EV exceeds minimum SOC of EV fleet
                    Provide energy until the demand is satisfied or eaches minimum SOC.
                    IF Energy demand is fulfilled
                       Update SOC of EV
                    ELSE Require energy from other sources.
        5:             IF Energy stored in PHS exceeds minimum SOC of PHS
                          Provide energy until the demand is satisfied or reaches minimum SOC
                          IF Energy demand is fulfilled
                             Update SOC of PHS system
                          ELSE Require energy from other sources
        6:                   IF Hydro power system have energy to supply
                                Provide energy until the demand is satisfied or until all stored
                                energy is supplied; Update energy availability in Hydropower
                                IF Energy demand is fulfilled
                                   Update energy availability in Hydropower
                                ELSE Require energy from other sources
        7:                         IF Importing energy is feasible
                                      Import energy until the demand is satisfied or maximum export
                                      limit  is reached
                                   ELSE Energy import limit has reached
                                      Indicate 'Energy shortage'
                                   END
                                END
                             ELSE
                                Move to step 7
                             END
                          END
                       ELSE
                          Move to step 6
                       END
                    END
              ELSE
                 follow step 5
              END
           ELSE $E_B$ is less than zero; shows higher RE generation than energy demand
              IF The SOC of EV fleet is below maximum SOC of EV fleet
                    Charge EV fleet until EV fleet reach maximum SOC or until excess energy is stored
                    Update SOC of EV fleets
(continuing**)
```

Fig. 5. Pseudo-code of the developed model in Simulink.

Comparing the average energy exchange from the last decade with the last 6 years, where the rapid increase of RE is seen, we can observe that the import/export has been relatively stable, from *Appendix 1*. With energy import, the deviation between the 10-year and 6-year average data is 0.6 % and for energy export, the deviation is 1.2 %. Considering the smaller deviation, the model follows the distribution from the 6-year average data to limit the monthly import and export. However, the total import/export can increase in the future as other countries are also in an energy transition phase.

```
(continuing**)
            IF There is surplus energy remains after storing it in EV batteries
8:              IF The SOC of PHS is below maximum SOC of PHS system
                    Store energy until PHS reach maximum SOC or until excess energy is stored
                    Update the SOC of PHS system
                    IF There is surplus energy remains after storing it in PHS
9:                      IF Energy export is possible
                            Export the excess energy;
                        ELSE Energy export is impossible or export limit has reached
                            Indicate 'Excess energy'
                        END
                    ELSE
                        Update the SOC of PHS system
                    END
                ELSE
                    follow step 9
                END
            END
          ELSE
              follow step 8
          END
       END
10: Estimate system self-sufficiency, hourly reliability, and energy trade of the different
    configuration
END
```

Fig. 5. (*continued*).

2.5. Modelling of sustainable energy system

To analyse V2G influence and high penetration of RES and ESS, a model is developed in the Simulink/MATLAB interface. The model includes RES (PV, wind energy, HP, other RES), non-RES (oil and natural gas), ESS (EV, PHS), and energy consumption profiles as mentioned in the previous sections. The hourly energy demand, hourly energy generation from RES and the initial (SOC) of ESS are the inputs to the model. The input profiles include the energy losses during electricity generation and consumption. EVs are considered the primary ESS and PHS is the secondary ESS. V2G satisfies energy storage requirements for a short-term period and PHS satisfies long-term energy storage requirements. Considering both charging and discharging cycles, the round-trip efficiency is 87 % for EVs and 80 % for PHS systems. The model output includes excess energy generation, energy shortage, hourly self-sufficiency, system self-sufficiency and SOC of ESS. Fig. 5 shows the pseudo-code of the model developed in Simulink for this study.

The initial step of the simulation is to estimate the energy balance from the inputs. The energy balance (E_B) is different from the total energy demand (from load profile and energy for EV) to the energy generation from RES. Equation 1 shows the calculation of E_B. Introducing the energy consumption by EV as an individual variable allows the model to estimate the total energy demand for transportation based on the input. Equation 2 shows the calculation of energy demand for transportation.

$$E_B\,(t) = (load\ cons.(t) + E_{EV}(t)) - (Wind\ energy\ (t) + PV(t)) \tag{1}$$

$$E_{EV}\,(t) = Average\ energy\ cons./km \times distance\ travelled \times Total\ EV \times EV\ distribution \tag{2}$$

'*t*' represents the time step (hours) of the simulation. The energy balance can be positive – which represents more energy demand than a generation from RES, negative – which represents higher energy generation from RES than demand and zero energy balance – where demand is equal to RES energy generation. During positive energy balance, the model extracts the missing energy from ESS. The initial energy is taken from EV and if more energy is still needed, PHS delivers maximum discharge each hour. Even if more energy is required, HP delivers the maximum possible energy in that hour. The missing energy after using ESS and HP is considered an energy shortage. During negative load balance, the RES system more energy than energy demand. This additional energy is stored in EV first and then on PHS until both ESS reach maximum SOC. Any additional energy available is termed excess energy. The model considers this excess energy as wastage, but in real life, it is possible to use this excess energy for other applications or energy

Table 3
Model variables that are assumed to be constant.

Variables	Values
PV capacity factor	13.65 %
Wind capacity factor	23.6 %
Average travel distance	49 km
Average energy consumption	220 Wh/km
SOC_{EV} Initial	50 % of total SOC_{EV}
SOC_{EV} Min	10 % of total SOC_{EV}
SOC_{EV} Max	90 % of total SOC_{EV}
Battery capacity	100 kWh
SOC_{PHS} Initial	70 % of the capacity
SOC_{PHS} min	30 % of the capacity
SOC_{PHS} max	100 % of the capacity

trading purposes. To estimate the SOC of EV during each hour, initially, the model identifies the SOC share of parked and moving vehicles through equations 3 and 4.

$$m_s\ (t) = EV\ driving\ distribution \times total\ EV\ fleet\ capacity \tag{3}$$

$$p_s\ (t) = (1 - EV\ driving\ distribution) \times total\ EV\ fleet\ capacity. \tag{4}$$

where $SOC_{EV\text{-}x}$ represents the SOC of the EV fleet at the beginning of the time period. During energy extraction or vehicle movement energy is taken from the battery and the final SOC of the EV at that particular hour is represented by $SOC_{EV(x+1)}$. This $SOC_{EV(x+1)}$ from the previous hour becomes the $SOC_{EV(x)}$ for the current hour, which is indicated by equation (5). Based on the maximum and minimum SOC given as input to the model, the model estimates the energy available ($E_{ava\text{-}EV}$) and storage capacity available ($S_{ava\text{-}EV}$) in EV through equations (6) and (7).

$$SOC_{EV-x}(t) = SOC_{EV-x+1}(t-1) \tag{5}$$

$$\mathrm{E}_{\mathrm{ava-EV}}(\mathrm{t}) = \mathrm{p_s}(\mathrm{t}) \times \mathrm{Cap}_{\mathrm{T-EV}}\ (\mathrm{SOC}_{\mathrm{EV-x}}(\mathrm{t}) - \mathrm{SOC}_{\mathrm{EV-min}}) \tag{6}$$

$$\mathrm{S}_{\mathrm{ava-EV}}(\mathrm{t}) = \mathrm{p_s}(\mathrm{t}) \times \mathrm{Cap}_{\mathrm{T-EV}}\ (\mathrm{SOC}_{\mathrm{EV-max}} - \mathrm{SOC}_{\mathrm{EV-x}}(\mathrm{t})) \tag{7}$$

Where $Cap_{T\text{-}EV}$ is the total battery capacity provided by the EV fleet. EVs provide energy to the grid during positive load balance if E_{ava-EV} is positive for that period. The energy extracted from EV is represented by E_{EX}. While EVs store energy in the batteries during negative load balance if S_{ava-EV} is positive. The energy stored in the EV is represented by E_{ST}. Upon successful energy injection into the grid/energy storage, the SOC of the parked vehicle gets updated, as in Equation (8). Equation (9) shows the SOC of moving vehicles after the travel of each hour. Finally, the SOC of the total EV fleet at the end of each hour is estimated through equation (10).

$$SOC\_P_{EV(x+1)}(t) = \left\{ \begin{array}{l} if E_B < 0 : ((p_s(t) \times Cap_{T-EV} \times SOC_{\mathrm{EV-x}}(t)\ ) + E_{ST})/Cap_{T-EV} \\ if E_B > 0 : ((p_s(t) \times Cap_{T-EV} \times SOC_{\mathrm{EV-x}}(t)\ ) - E_{Ex})/Cap_{T-EV} \end{array} \right\} \tag{8}$$

$$SOC\_M_{EV(x+1)}(t) = ((m_s(t) \times Cap_{T-EV} \times SOC_{\mathrm{EV-x}}(t)\ ) - E_{EV}(t))/Cap_{T-EV} \tag{9}$$

$$SOC_{x+1}(t) = p_{share}(t) \times SOC\_P_{EV(x+1)}(t) + m_{share}(t) \times SOC\_M_{EV(x+1)}(t)) \tag{10}$$

For PHS, the model estimates the SOC during each hour using the same equation. Instead of EV parameters, PHS parameters such as SOCPHS will be used, and the model does not consider the moving EV variables to estimate the SOC of PHS. Finally, the system's self-sufficiency and the hourly reliability of the system are calculated. Hourly reliability and self-sufficiency serve as key metrics to evaluate the performance and stability of the energy system under different scenarios. Hourly reliability is determined by analysing the system's ability to meet electricity demand consistently throughout each hour. This involves comparing the actual electricity generation, including both renewable and energy storage sources, with the demand. If the renewable and energy storage sources fail to meet the demand, energy will be taken from external sources, and reliability for those hours will be zero. The reliability metric reflects the percentage of hours in which the system successfully satisfies the demand without any shortfall. In simulation scenarios with energy import, the model compares the actual electricity availability, including renewable energy, energy storage sources, and electricity import, with the demand. Self-sufficiency measures the system's capability to fulfil its electricity demand solely from internal renewable energy and energy storage, without relying on external support. It is calculated as the percentage of total energy demand met through in-house renewable energy generation. Equations (11) and (12) represent the calculation of hourly reliability and system self-sufficiency.

$$Hourly\ reliability\ = \sum_{1}^{8760} \left\{ \begin{array}{c} if\ \ (E\ bal._{PHS}\ +\ E_{HP}) < 0;\ 0 \\ if\ \ (E\ bal._{PHS} +\ E_{HP}) \geq 0; 1 \end{array} \right\} /8760 \tag{11}$$

$$System\ self - sufficiency\ = \frac{Total\ energy\ produced}{Total\ energy\ required} \times 100 \tag{12}$$

2.6. APPLICATION OF THE MODEL

The primary application of the model is to analyse the energy goals of Spain in 2030 and 2050 with EV as ESS through V2G. The analysis consists of two main operational scenarios for Spain,

1%1 To fulfil 42 % of the energy requirement with RES and ESS (2030 RE goal).
2%1 To satisfy 97 % of the energy requirement with RES and ESS (2050RE goal).

In the first scenario, the model simulates the RES installation required to meet the energy goals of Spain in 2030. The simulation is structured so that the RES and ESS system delivers 42 % of the total load. Fossil-based power plants deliver the rest. Spain has already decided to shut down the nuclear power plants starting in 2027. The electricity production from nuclear power plants will be replaced by RES [55]. By 2030, Spain aims for a 23 % reduction in greenhouse gas emissions compared to 1990 levels; a 42 % share of renewables in energy end-use; a 39.5 % improvement in energy efficiency; and a 74 % share of renewables in electricity generation RES [55]. Spain also targets a significant buildout of new RES to reach 74 % of electricity generation by 2030, notably wind and solar. To estimate the PV-wind share, the mode assumes varying PV installations (from 100 to 400 GW). Then the model computes the necessary wind energy installation to meet the energy demands without any energy shortage. Planning to have 2.7 to 3.6 million EVs in 2030, using a portion of this EV for energy storage through V2G can benefit Spain. For the analysis of 2030 scenarios, we assume a total EV fleet of 3.15 million EVs for V2G purposes.

In the second scenario, the simulation identifies the RES installation required to provide 97 % of energy requirements from RES and ESS. For 2050, Spain's energy goal is to make the country climate neutral, with 100 % renewable energy in the electricity mix and 97 % in the total

Table 4
Comparison of results from Energyplan and Simulink (error).

Parameter	Energy plan	Simulink model*
Electricity import (TWh)	1.53	1.54 (0.6 %)
Electricity Export (TWh)	5.51	5.33 (3.2 %)
Hourly reliability (%)	77.01	75.97 (1.3 %)
System Self-sufficiency (%)	85.02	84.92 (0.1 %)

*(difference in percentage w.r.t the results from Energyplan within the brackets).

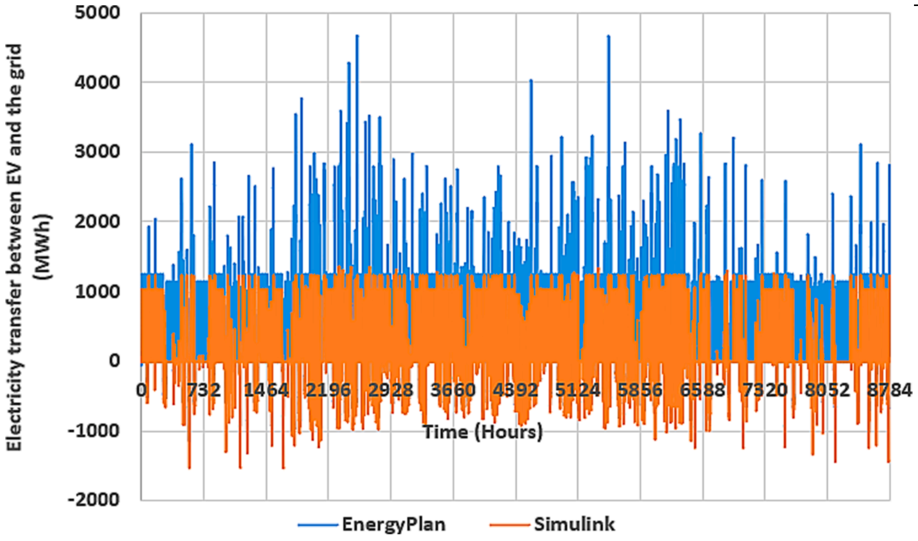


Fig. 6. Electricity transfer between EV and the grid over the simulation period.

energy mix RES [55]. In 2050, we assume 60 % of the total vehicles will be EVs, rest will be powered by hydrogen/biofuel without any emissions. Through these two scenario analyses, we can display the possible renewable energy installation and ESS requirement and V2G influence to reach those energy goals. For the analysis, we assume that the total EV fleet is available for V2G and is connected to the grid through bi-directional chargers except when it is operational. Table 3 shows the variables assumed to be constant throughout the studies, as explained in the former sections.

2.7. Sensitivity analysis and model validation

To study the influence of the number of EVs, the impact of V2G technology and RES installation on energy production and storage, sensitivity analyses (systematically varying variables to understand their impact on results) were done for each of the two main scenarios. The analysis focuses on

i. RES installation and excess energy generation
ii. Analysis on the influence of EVs as primary energy storage system and sensitivity analysis on EV volume
iii. Sensitivity analysis on V2G acceptance and battery availability

We study the variables because these would have the most prominent outcome on the potential contribution for energy balancing of V2G. The simulation focuses on meeting 42 % and 97 % system self-sufficiency to meet future energy goals. Each of these studies portrays the influence of each variable on the respective energy goals.

Before performing the analysis, model validation is necessary to ensure the model's reliability. The ISO 9000:2015 standards [83] explain the validation of model as a "*through the provision of objective evidence, that the requirements for a specific intended use or application have been fulfilled; the objective evidence needed for a validation is the result of a test or other form of determination, such as performing alternative calculations*".The International Energy Agency [84] also quotes that "*model verification and validation is to ensure the computer program of the computerised model and its implementation are correct*". For this study, we follow the 'model validation by comparison technique', a technique suited to models of future scenarios when model validation through comparison with empirical data is not an option [85].

Further, Smiatek et al [86] state about the validation process that '*if the simulation model output data and the real-world output data are consistent with each other, the simulation model is not rejected, but neither is it accepted or 'proven true'*. *It is provisionally accepted as 'valid' because it has not been falsified'* [86,87]. Wang & Grant and Rykiel forward the notion that validation "*means that a model is acceptable for its intended use because it meets specified performance requirements.*" [88,89]. Collier et al [90] mention in their study that validation is a process of comparing the correspondence between model outputs and system behaviour. Sargent et al [91] explain the process of validation as "*substantiation that a computerized model within its domain of applicability possesses a satisfactory range of accuracy consistent with the intended application of the model.*" Furthermore, Refsgaard & Henriksen's [92] support validation by comparison method. They explain that a "*Model code may be verified within given ranges of applicability and ranges of accuracy, but it can never be universally verified. Similarly, a model may be validated, but only with reference to site-specific applications and to pre-specified performance criteria.*" Based on this, they arrive at the finding that a "*model's validity will always be limited in terms of space, time, boundary conditions and types of application*" [92].

The previous sources highlight model validation by comparison proves as one of many ways to validate models. Based on these, we define the model validation process as a process that involves confirming that the model accurately represents the system, provided that the system generates enough evidence in the form of results that are comparable, and the model results align with the observed or expected data. Following the ISO 9000:2015 definition, we emphasise the importance of providing objective evidence to confirm that the model's requirements for a specific intended use have been met. Østergaard et al [85], Smiatek et al [86], Collier et al [90] and other references above further supports his method by highlighting that validation is not a universal process but is contingent upon specific applications, performance criteria, and contextual constraints such as space, time, and boundary conditions. Furthermore, the studies suggest as long as the performance of the model can generate objective evidence in terms of results and can meet expectations from an operational scenario, the model can be considered reliable and fit for the task it was created for.

However, it is necessary to find the right model to compare and perform the process. The model which we employ for comparison needs to be valid, reliable, and widely used. The literature by Østergaard et al [85] explains a comprehensive exploration of the validation process for Energyplan software and its authenticity in performing energy systems simulation. With over 73 articles published with the results from Energyplan software, the model is considered valid and reliable. we validate our model using validation by comparison techniques against the Energyplan software (V – 16.22) itself.

We simulate identical operation conditions and compare the results to examine the differences in results. Energyplan software is an open-source energy system simulation model developed in 2006 and is still in use for 100 % of RE studies [93]. Over the years, more than 73 articles have been published using the results from Energyplan software which is still considered one of the most used energy systems model software. Even though Energyplan software has been widely used in the past, for V2G studies, the model has limited flexibility to explore a wide range of inputs for V2G service, thus limiting the diverse operational scenarios for the V2G operation. The limitation in the software with V2G simulation is further discussed in section 3.1. For the validation process, we simulate a 100 % RE scenario with both models. Custom-made load profile, PV and wind profile and EV driving profile for a year are given as input. *Appendix 2* shows the inputs to both simulation models. For the validation process, the annual electricity demand is given as 7 TWh. In addition to the electricity demand, the model adds the electricity demand from EVs for travelling. The model considers one million EVs with 80 kWh battery packs, consuming 220 Wh/km. Over the course of a day, each EV is designed to travel 49 km on average. Out of one million EVs, with a small portion supports V2G, which provides an energy storage capacity of 10 GWh in total. Since the primary goal of this study is to identify the potential of EV batteries to replace other energy storage systems, only EV battery is used for energy storage purposes in both models. As the validation process aims to compare the results from both software, all the inputs given for the validation testing are arbitrary. Section 3 discusses the results from the analysis and validation process.

3. Results

The simulation model made in Simulink/MATLAB software helps to simulate various parametric studies, as mentioned in Section 2.5. The model estimates the excess energy production from the RES and the energy shortage through the high penetration of the RES. Also, the model computes the system's self-sufficiency, hourly reliability, energy exchange and SOC of ESS on the system. The annual PV and wind electricity production and the electricity consumption profile are given as input along with the initial SOC of EV and PHS systems, as explained in section 2.5.

3.1. Model validation by comparison technique

The model validation follows model validation by comparison technique, by comparing the results from the Simulink model with results from the open-access Energyplan software [93]. A 100 % RE scenario is tested where the electricity demand is 7 TWh excluding the demand for EVs. The load profile, EV driving profile, and PV and wind energy generation profiles were given as input (*Appendix 2*). The simulation duration is 8784 h (leap year). Table 4 shows the results of the simulation from both simulation models.

Table 4 shows the simulation results from both simulation models. From the results, we can observe that the deviation in electricity import, and export, hourly reliability and system self-sufficiency are very small between the two simulation models. With Energyplan software, the scenario imports 1.53 TWh and exports 5.51 TWh energy, while 1.54 TWh import and 5.33 TWh energy export potential are seen in the Simulink model with a deviation of 0.6 % and 3.2 % respectively. With Hourly reliability and system SS, the deviation in results is very small for the Simulink model with respect to the Energyplan model with 1.3 % and 0.1 % for hourly reliability and SS respectively.

In the results, we can observe a 3.2 % higher electricity export from the Simulink model. With the Simulink model, the maximum energy transfers between the EV and the grid are limited by the charger power. With one million EVs providing 10 GWh storage capacity, the number of vehicles that participated in V2G, also called the V2G acceptance rate would be 12.5 %. With an 11-kW charger and 12.5 % of total EV support, the maximum electricity transfer possible between the grid and the EV would be 1375 MWh. When the Energyplan model transfers electricity of more than 1375 MW in 1 h, the Simulink model limits the transfer to 1375 MW and exports the rest of the electricity. This is the reason for higher energy export in the simulation model. This leads to reduced hourly reliability and SS. Nevertheless, it is vital to consider charger power during the analysis, as charger power determines the maximum energy exchange possible between the EV and the grid. Fig. 6 shows the electricity transfer between the grid and EV from both simulation models.

Both the Energyplan and Simulink simulation model facilitates the dynamic nature of the vehicle moving distribution. Appendix 3 shows the simulation results and a comprehensive description of the dynamic nature of vehicle movements and simulation. Appendix 4 shows the Hourly reliability, self-sufficiency, energy import and export from both models during each hour. Comparing the results from the Simulink and Energyplan model, including the hourly energy flow, hourly reliability and self-sufficiency, the Simulink output succeeded in capturing system behaviour and giving corresponding results, higher satisfactory accuracy in results (error less than 3 %) and finally providing objective evidence by comparing with a validated model - Energy plan software. Considering all these facts, the model meets the expectations discussed in section 2.7 and is considered validated.

Despite the close match between the results with Energyplan software, the Simulink model includes a number of functions, for conducting a more comprehensive V2G study, that the Energyplan model lacks. In contrast to Energyplan's model, which is based on the battery capacity and the patterns of EV movement, Simulink's model offers a range of variables that can be customised to simulate specialised operational conditions. Among them are the following:

- Charger Power Control: where the user can input the charger power. This feature enables the simulation of different charging scenarios, including various charging rates.
- Average EV Energy Consumption: Depending on the type of vehicle, the amount of energy consumed can be changed. This reflects the real-world variations in EV efficiency and driving patterns, making simulations more accurate and relevant.
- EV Share in the Fleet: Simulink allows users to model different proportions of EVs in the total vehicle fleet. This flexibility facilitates understanding the implications of different adoption rates and fleet compositions on V2G operations.
- V2G Acceptance Rate: Users can study the effects of varying V2G acceptance rates, which reflect the willingness of EV owners to participate in grid services. This facilitates assessing the feasibility and impact of V2G at different adoption levels.
- SOC Constraints: The ability to set minimum and maximum State of Charge (SOC) levels for EV batteries, which can charge and discharge. It allows the exploration of different strategies for managing battery health and grid support.
- Customizability and Variable Analysis Conditions: Simulink allows a wide range of parameters and an array of conditions to suit the specific study objectives. This level of customization is invaluable when analysing V2G systems under varying conditions.

This versatility allows for in-depth analysis under various scenarios, with the flexibility to modify each of these variables to suit specific research conditions.

3.2. Scenario 1: 42 % energy from res - to fulfil the 2030 renewable goal

Scenario 1 in the study analyses the influence of V2G to support the 2030 energy goal of Spain. In 2030, Spain intends to generate 42 % of the total energy from RES. The rest of the generation is from non-renewable sources. Through this analysis, we identify the influence of EVs as energy storage, along with the RES installation and secondary ESS systems required to meet 42 % of the yearly energy requirement in

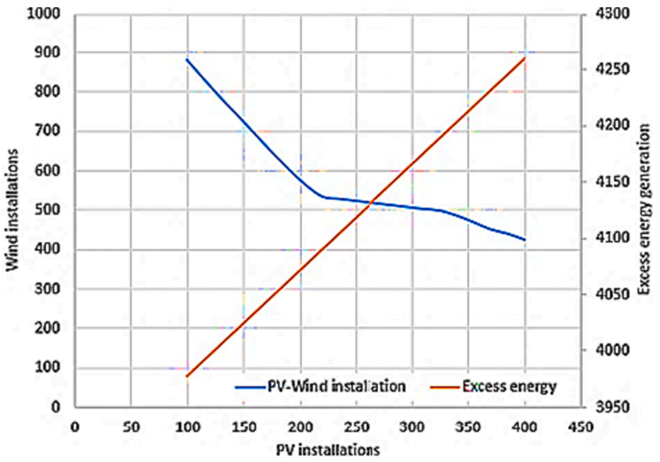


Fig. 7. Renewable energy installations required without external support to meet 2030 demands.

Spain. While meeting the 42 % requirement from RES, the rest of the electricity is from oil and natural gas as explained in Table 2. Scenario 1 analysis is completed in 3 stages, as follows.

3.2.1. *RES installation and excess energy generation*

In the initial stage of Scenario 1 analysis, we determine the RES installation require to meet the demands in Stage 1. This analysis examines the PV and wind installation ratio to meet the demand with 100 % self-sufficiency and hourly reliability. With 100 % self-sufficiency and hourly reliability, the model implies that RES (PV/Wind) deliver their share without any additional external support. One of the drawbacks of such an approach is that if the total supply is short of 1 kWh, the model advises increasing the installation. This can be solved by including energy imports from neighbouring countries.

In this analysis, we analyse all these options, where we estimate the RES installation requires to meet 100 % self-sufficiency without any external support and with energy trade possibility, using EV as the primary energy storage option. To estimate the PV-wind share to support the demand, we assume PV installation (from 100 GW to 400 GW) and the model calculates the wind energy installation to meet the energy demands. In addition to the wind installations, the model also calculates the energy flow, excess energy generation, energy shortage and SOC of different technologies. Fig. 7 shows the simulation results of the PV and wind ratio with zero energy shortage (without external support and import). For this analysis, the PHS capacity is 5535 MW, which is the current available PHS capacity of Spain and uses 80 % battery availability for V2G technology, with 3.15 million EVs in 2030.

From Fig. 7, we can observe that the total required installation ranges between 800 GW and 1000 GW to support a 42 % share of RES in

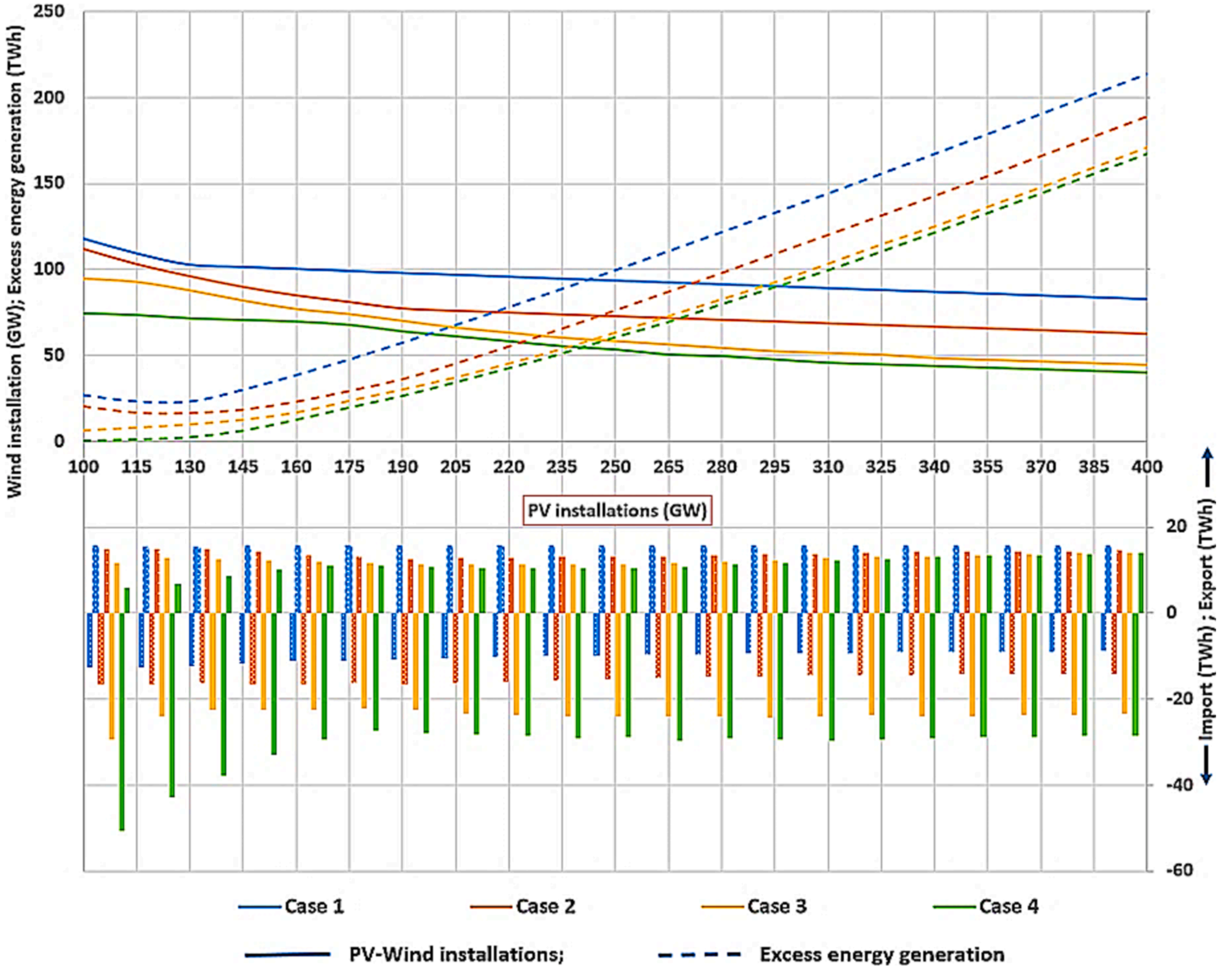
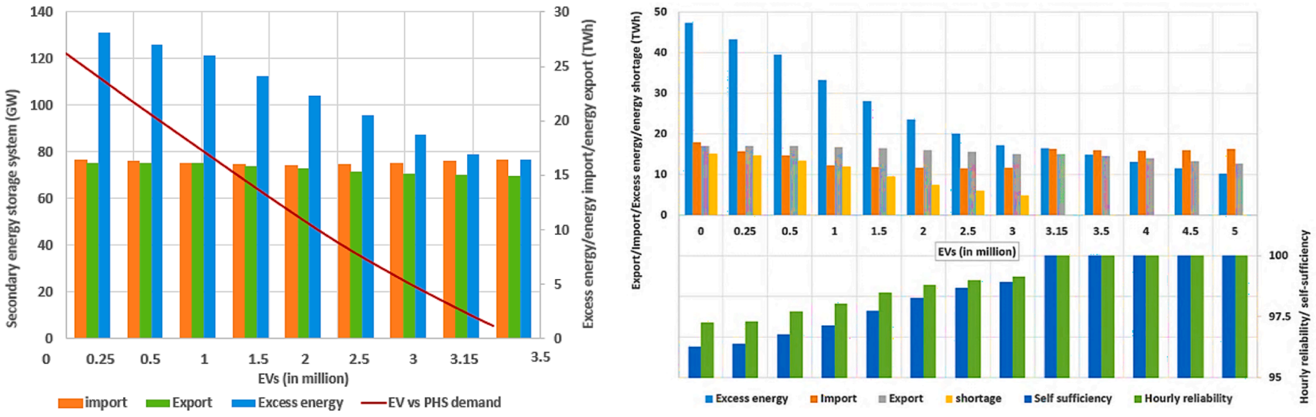


Fig. 8. Renewable energy installation required with energy import to meet 2030 demands. Case x: [import, export]. Case 1: [10 TWh,17 TWh], Case 2: [18.8 TWh,17 TWh], Case 3: [30 TWh,17 TWh], Case 4: [50 TWh,17 TWh].



(a) Number of EVs vs secondary ESS

(b) Impact of change in EV volume

Fig. 9. Influence of change in EV volume as the primary energy storage system.

the energy mix. The higher RE requirement is because of high load demand during certain hours. In such conditions in real life, energy is brought in through import or operating reserve power plants. Since the model does not have any reserve power plants and energy shortage and import are set to zero, the model increases the RES installation (PV and wind installations) to meet the peak demands.

With renewable energy import from neighbouring countries, it is possible to reduce the RES installations without depending more on reserve power plant which operates on non-RE sources. Considering the electricity import/export, in the past decade, the data shows the highest electricity import in 2018 with 24 TWh with an average of 19 TWh [69]. The highest export was recorded in 2022 with 28 TWh with an average of 17 TWh over the last decade [69]. In this study, we emphasise electricity imports, as importing electricity helps to reduce the installations in Spain. Using a linear regression model, an estimate of 9 TWh import and 21 TWh export can be expected in 2030. Nevertheless, future forecasting is highly unpredictable because the energy sector is going through a transition phase. Due to this unpredictability and based on average and maximum import over the decade, we established 4 cases with different energy import values. Case 1 with the maximum import of 10 TWh in 2030, as that of predicted output from linear regression. Case 2 with the maximum import of 19 TWh in 2030, as that of the average from last decade. Case 3 and case 4 test a hypothetical situation where Spain imports more energy than its highest import in the last 10 years. Case 3 has a maximum import of 30 TWh import in 2030, which is 25 % more than the highest import and case 4 has a maximum import of 50 TWh import in 2030, which is 100 % more than the highest import in the last decade. For export, the model considers the average value of 17 TWh for all the cases. Fig. 8 shows the simulation results with energy import and export, for the zero-energy shortage situation.

From the results in Fig. 8, we can observe that with an energy import of 10 TWh to 50 TWh, the total required installation reduces from a total of 800 – 1000 GW without any external support to 300 – 400 GW. From the results, we can observe that for any of the cases, the drop in wind installations is very small when PV installation increases from 100 to 400 GW. This implies that PV needs to be combined with other sources to reach RE targets. Considering different cases, in this study, we choose to follow case 2 with an energy import of 18.8 TWh and an import of 17 TWh. Even though various organisations perform 100 % renewable energy studies in various parts of the world, none of the studies explicitly predicts the energy exchange market for Spain in 2030 or 2050 [4,10,18,94]. This is because of the highly uncertain variables in the energy sector. Due to this uncertainty on future energy exchanges, performing further studies with average energy exchange value is a rational choice.

From Fig. 8, we can observe that for each installation, the excess energy generation varies. Excess energy is the energy available after energy imports. To identify the best possible installation combination, we choose the PV-wind installation with the least excess energy generation. For case 2, 120 GW of PV with 100 GW of wind energy gives the least excess energy generation of 16.4 TWh. Considering case 1, the best possible combination is 115 GW - PV with 110 GW of wind energy installation. We can see that the increase in installation is 5 GW to offset the import of 8.8 TWh. In case 1 Spain acts as a net energy exporter. As the energy import rises, as in cases 3 and 4, the best possible combination of PV and wind is 100 GW PV and 94 GW wind installation and 100 GW PV with 74 GW wind installations, respectively.

3.2.2. Analysis on the influence of EVs as primary energy storage system and sensitivity analysis on EV volume

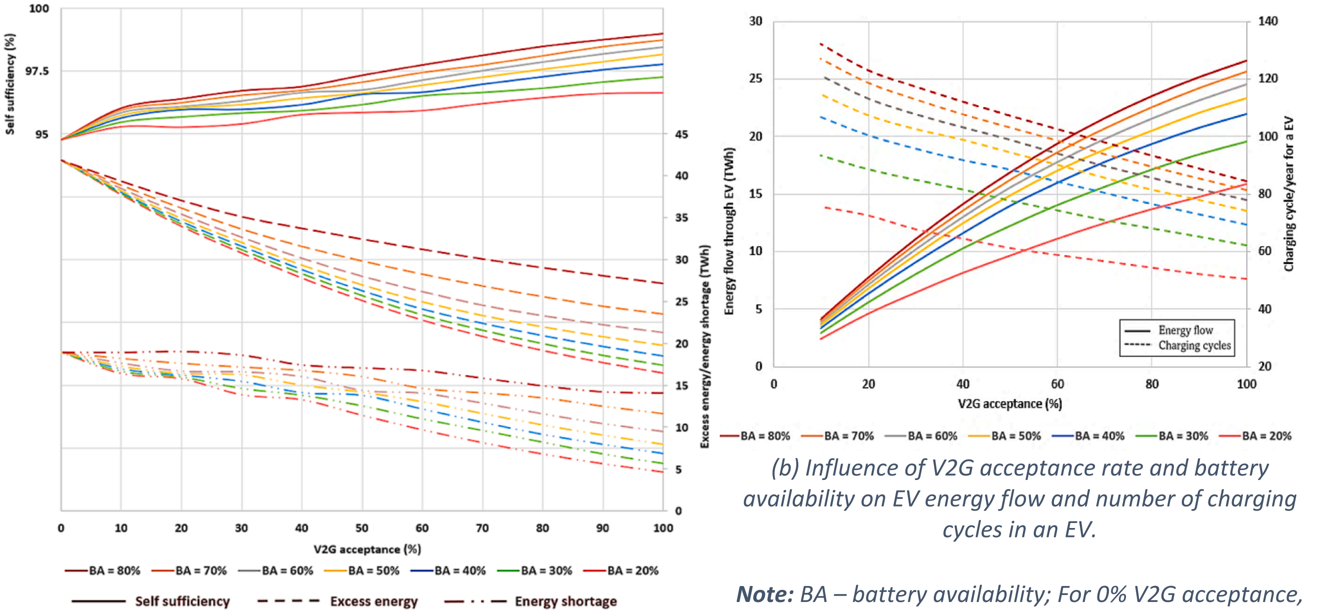
As with other European countries, Spain is also in the midst of a transition in its transportation sector. In order to replace fossil-fuelled vehicles with green alternatives, EVs and biofuel vehicles are becoming more popular. This analysis examines the benefits of having EVs as energy storage devices. By comparing EV as ESS, we estimate the total ESS replaced by EV through V2G. This study considers PHS as a secondary ESS. The secondary storage represents all the storage available in Spain. It is not necessary to increase the capacity of PHS in order to meet the secondary capacity requirement of an ESS from this study; there can be another storage system installed in its place.

This analysis has two main purposes,

1. To identify the amount of ESS required if EV is not employed.
2. Analyse how changes in EV numbers influence the total energy flow and system performance.

From the previous analysis, we identified 120 GW of PV and 100 GW of wind as the best combination to have zero energy shortage with 18.8 TWh import and 17 TWh export. Also, we considered 3.15 million EVs for energy storage. In this analysis, keeping all the other variables constant, we analyse a range of EV numbers in the fleet that provide energy storage options through V2G. From 0 EVs to 5 million EVs (which is the most optimistic forecast for EVs in 2030) and the model identifies the secondary energy storage required to meet zero energy shortage in each case. Fig. 9a shows the simulation results from the analysis. Fig. 9b shows the impact of change in EV volume. Forecasts always have uncertainty, and this uncertainty can cause errors in the forecast values. In 2030, different forecasts estimate different EV volumes ranging from 2 million to 5 million EVs. To identify the influence of EV volume on results, we perform a sensitivity analysis on EV volume ranging from 0 EVs to 5 million EVs in the 2030 scenario.

Fig. 9a shows the importance of EVs as an energy storage system and ESS demand if EVs are not used for energy storage purposes. Focusing on the 2030 scenario with 3.15 million EVs and 5535 MW PHS installation,



(a) Influence of V2G acceptance and BA on system performance

(b) Influence of V2G acceptance rate and battery availability on EV energy flow and number of charging cycles in an EV.

***Note:** BA – battery availability; For 0% V2G acceptance, the EV energy flow and charging cycle for V2G is zero.*

Fig. 10. Sensitivity analysis on V2G acceptance and battery availability.

the excess energy generation is 16 TWh. As we decrease the number of EVs, to maintain the same self-sufficiency, hourly reliability and energy shortage point, the system needs more secondary ESS systems. If no EV participates in V2G, the approximate requirement of ESS is 122 GW of new storage units. If EVs replace fossil cars, at a slower pace, e.g.: 2.5 million EVs in 2030, to have 100 self-sufficiency systems which provide 42 % of energy from RES, the system needs 25 GW of new storage units. Fig. 9b shows the impact of the change in EV volume. When EV growth is slower than anticipated, with 2.5 million EVs in 2030, without any new energy storage units in the system, the self-sufficiency decreases. From Fig. 9b, we can observe that self-sufficiency decreases to 98.6 % with an hourly reliability of 99 %. With no EV connected to the grid through V2G, the system reliability reduces to 96.2 % with hourly reliability of 97 %.

3.2.3. Sensitivity analysis on V2G acceptance and battery availability

V2G technology provides exceptional energy storage possibilities, using the batteries of electric vehicles. However, the balancing potential of V2G technology is dependent on several factors other than the technology itself [95]. One such factor is the V2G acceptance rate, which refers to EV user's willingness to participate in V2G services. Studies conducted in the past have shown that potential V2G adoption among EV users may be very low for a variety of reasons [96–99]. A lower acceptance of V2G reduces energy storage capacity and the number of vehicles connected to the grid. Further, range anxiety is another major barrier to V2G adoption [100,99]. Range anxiety is the fear that a vehicle does not have enough battery capacity left to travel the distance required to reach its destination in this analysis, we investigate the effects of these two prime variables on V2G's energy storage and flow capacity.

In the initial simulation, we assume a V2G acceptance of 100 % with battery availability of 80 %, with maximum SOC of 100 and minimum SOC of 10 %. In the analysis, we simulated different V2G acceptance rates, from 0 to 100 %, and battery capacity ranging from 20 % to 80 % reserved for V2G purposes. For the simulation, The PV and wind installations are 120 GW and 100 GW with 3.15 million EVs connected to the grid through a 7-kW bi-directional charger. Fig. 10 shows the results of the simulation. Fig. 10a shows the simulation results on the influence of V2G acceptance and battery availability on system performance and Fig. 10b shows the influence of V2G acceptance and battery availability on EV energy flow and charging cycles per year. Since the change in self-sufficiency is small, the self-sufficiency of the plot starts from 94 % on a different scale (on the Y axis).

From Fig. 10a, we can observe that the self-sufficiency of the RE system is declining as the V2G acceptance rate and battery availability drop. With a lower V2G acceptance rate, fewer EVs are connected to the grid for energy transfer. As a result of the reduction of EVs connected for V2G service, the total ESS capacity available through V2G decreases. This will reduce the storage potential of energy, especially during periods with high-RES energy generation and will decrease energy discharge during high-load periods. As a result of this, the excess energy generation and energy shortage increases as shown in Fig. 10a. This reduces the self-sufficiency and the hourly reliability of the system. While for the same V2G acceptance rate, a decrease in available battery capacity for V2G service also reduces the storage capacity through V2G service. This will result in the reduction of self-sufficiency and hourly reliability of the system.

Fig. 10b shows the change in energy flow through EVs and the number of charging cycles dedicated for V2G purposes for different operational scenarios. From the results, we can observe that as V2G acceptance or battery availability is reduced, the energy flow through EVs is also reduced. It is because of the reason discussed above, i.e., the change in total energy storage capacity. This will then reduce the maximum possible storage/extraction, and hence the energy flow. However, looking into the number of charging cycles each vehicle has to go through, for different V2G acceptance rates and battery availability, it can be observed that a low V2G acceptance rate puts more pressure on each vehicle. With 10 % V2G acceptance and 50 battery availability, each EV has to go through 115 full charging cycles as compared to 102 and 94 charging cycles with 30 % and 50 % V2G acceptance.

From the results, we can observe that with 50 % V2G acceptance and 50 % battery availability, we lose approximately 1.9 % self-sufficiency (hourly reliability – 97.9) as compared to the scenario with 100 % V2G acceptance and 80 % battery availability (hourly reliability – 99.8). The reduction in self-sufficiency is very small in this scenario. It is because of the smaller share of RES. With a 42 % share from RES, there are other flexible sources to support the grid. The results also show a 30 % V2G acceptance rate with 50 % battery availability helps to achieve

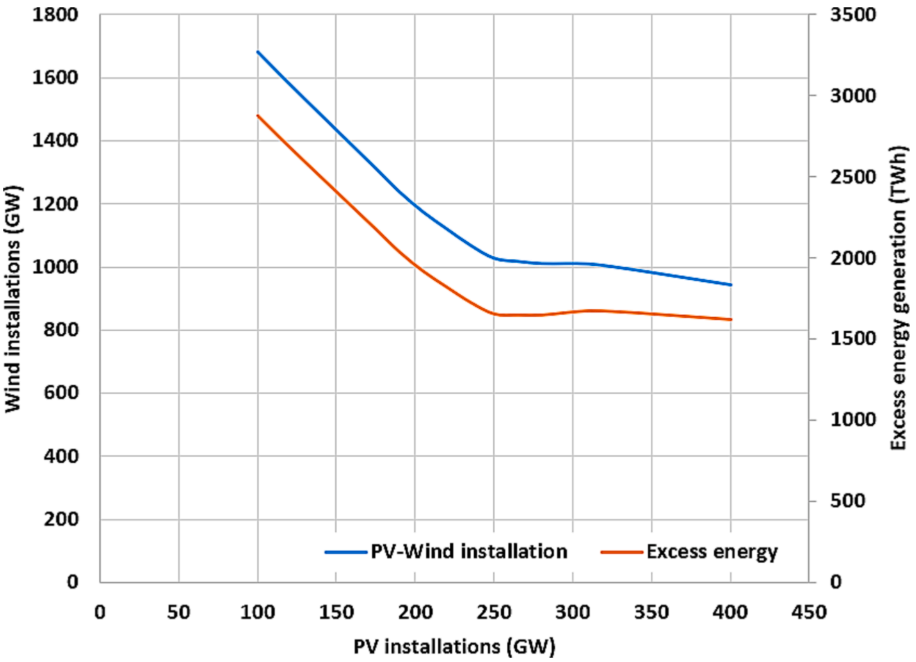


Fig. 11. Renewable energy installations required without external support to meet 2050 demands.

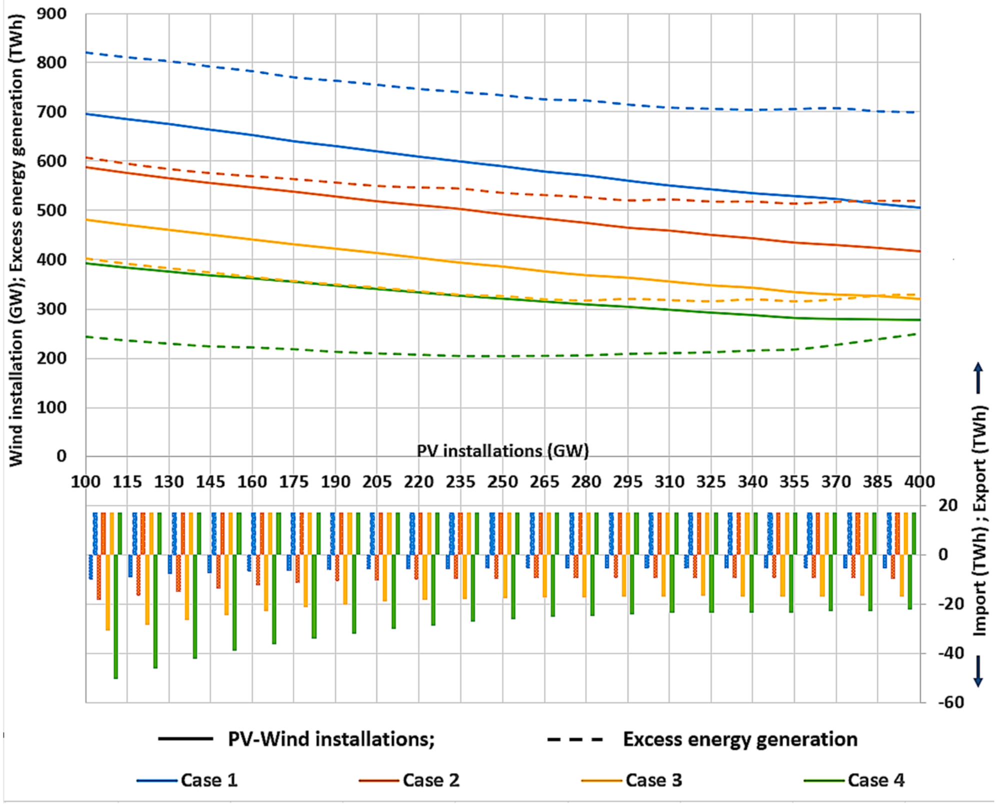
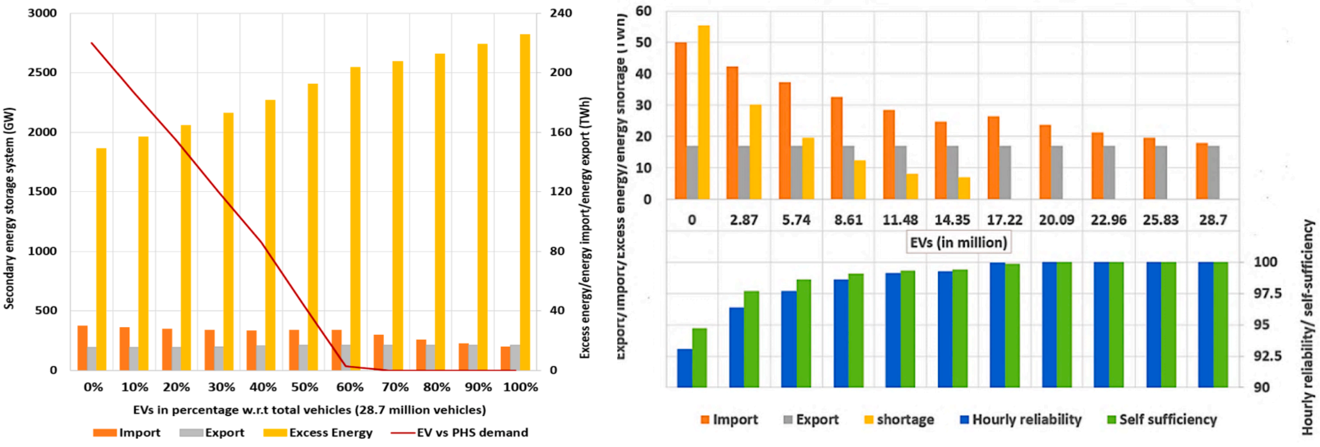


Fig. 12. Renewable energy installation required with energy import to meet 2050 demands. Case x: [import, export]. Case 1: [10 TWh,17 TWh], Case 2: [18.8 TWh,17 TWh], Case 3: [30 TWh,17 TWh], Case 4: [50 TWh,17 TWh].

97.32 % hourly reliability with 96.17 % system self-sufficiency. Subsequently, the study indicates that V2G services using EV batteries substantially can reduce RES intermittency issues, also if less than half of the owners are willing to be part of the V2G service.

3.3. *Scenario 2: 97 % energy from res - to fulfil the 2050 renewable goal*

Scenario 2 analyses the energy goals of Spain in 2050. In 2050, Spain intends to generate 97 % of the total energy from RES. While meeting the 97 % requirement from RES, the rest of the energy is from natural gas as explained in Table 2. In this scenario, we analyse RE installation and



(a) Number of EVs vs secondary ESS

(b) Impact of change in EV volume

Fig. 13. Influence of change in EV volume as the primary energy storage system.

excess energy generation, the influence of EVs as primary energy storage systems sensitivity analysis on EV volume and finally sensitivity analysis on V2G acceptance rate and battery availability for the energy system in Spain for 2050. The whole study is completed in three sections as follows,

3.3.1. RES installation and excess energy generation

In scenario 2, the initial analysis determines the RES installation required to meet the demands in 2050, which is 97 % of the total energy demand. As in section 3.2.1, in this study we analyse all these options, where we estimate the RES installation required to meet 100 self-sufficiencies without any external support and with energy trade possibility, using EV as the primary energy storage option. Similar to section 3.2.1, to estimate the PV-wind share to support the demand, we assume PV installation ranging from 100 GW to 400 GW and the model calculates the wind energy installation to meet the energy demands. In addition to the wind installations, the model also calculates the energy flow, excess energy generation, energy shortage and SOC of different technologies. For this analysis, the PHS capacity is 5535 MW, which is the current available PHS capacity of Spain, and we assume no new PHS storage is made after that. In 2050, the vehicles will be emission-free, but only a part of them will be EVs. The rest of the vehicles will be powered by hydrogen or biofuel. In this study, we assume 60 % of all vehicles will be EVs, which is 17.22 million EVs. Fig. 11 shows the simulation results of the PV and wind ratio with zero energy shortage with 100 % V2G acceptance and 80 % battery availability (without external support and energy exchange).

From Fig. 11, we can observe that the total required installation ranges between 1400 GW and 1800 GW to support a 97 % share of RES in the energy mix. 1400 GW is more than 10 times the current installation in Spain. Having such a large installed capacity, we can observe that the excess energy generation is between 1500 TWh and 3000 TWh, which is in the range of annual electricity demand of a country the size of Spain. This high excess energy generation is the result of high-RES installation, which helps to meet the high hourly energy demands. Since the model does not have any reserve power plants and energy shortage and exchange are set to zero, the model increases the RES installation of PV and wind to meet the demand.

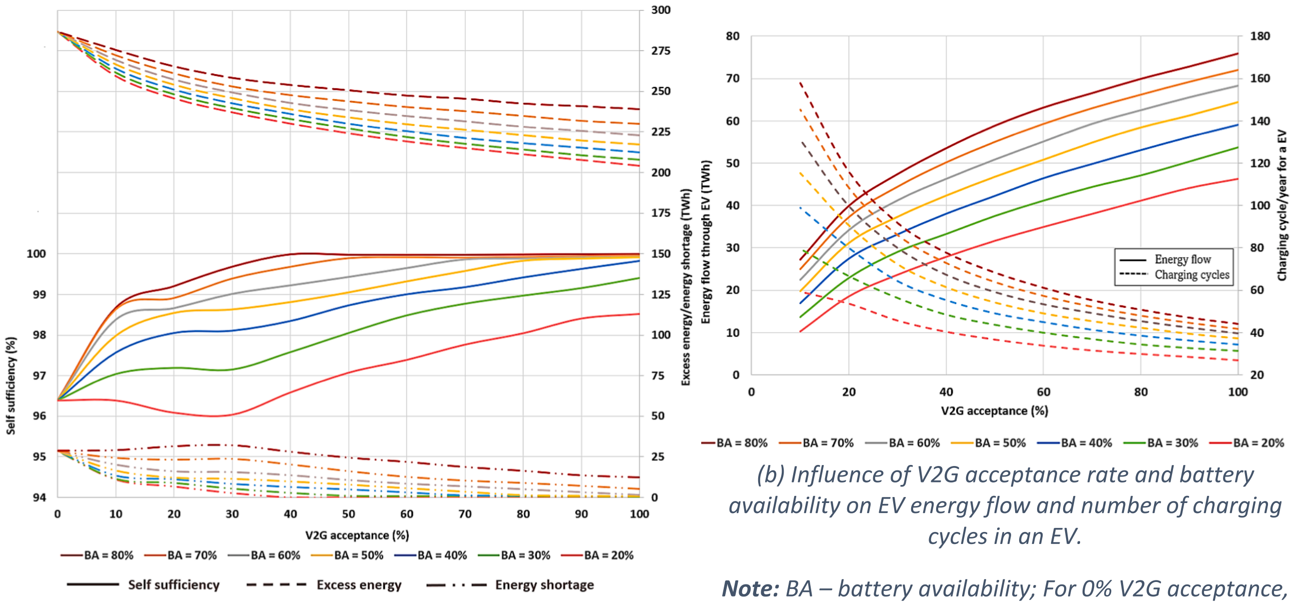
Considering the electricity import/export, we also consider the 4 cases as we have done in section 3.2.1. Case 1 with a maximum import of 10 TWh, Case 2 with a maximum import of 18.8 TWh, Case 3 with a maximum import of 30 TWh import and Case 4 with a maximum import of 50 TWh. The import energy has significant importance in the model, as based on the potential import, the model has the flexibility to reduce the RE installations. While energy export only influences the result of excess energy generation in the model, which has very less impact on other performance variables. Due to this, we consider a fixed export of 17 TWh (average export in the last decade). Fig. 12 shows the simulation results with energy import and export, for the zero-energy shortage situation.

Fig. 12 shows the simulation results with four different energy imports and export limits for the zero-energy shortage situation. From the results, we can observe that energy import helps to reduce the total RE installation. With case 1, the total installation is reduced from 1400 to 1800 GW without any import to less than 900 GW with 10 TWh import. This value further goes down to 700 – 800 GW installation with 18 TWh, to 600 – 650 GW with 30 TWh and 500 – 550 GW with 50 TWh import.

Nevertheless, the linear regression model identifies that the import could be zero in 2050, based on the past data. The past data used for linear regression only considers the past with fewer renewable sources and electrification processes. Since most of the countries turn to net zero emission states and RE-supported grid systems, the energy exchange would possibly increase, which in turn increases the import and export for a country. With 24 TWh imports in 2018, where the total RE share was less than 20 % of the total energy mix, we assume this can double in 2050. Since no report or article explicitly gives an import limit in 2050, the real import can increase or decrease. for further studies, we choose an annual import of 50 TWh and subsequent RE installations. Considering 50 TWh import, the best possible PV-wind combination is identified by looking into the least excess energy generation point. The combination of 235 GW PV and 328 GW wind installation gives the least excess energy of 204 TWh of electricity. Even though the excess energy generation is high, with one-fifth of the total demand, this excess energy can be used for producing hydrogen which can be further used, or for other purposes.

3.3.2. Analysis of the influence of EVs as primary energy storage system and sensitivity analysis on EV volume

This analysis focuses on examining the benefits of having EVs as energy storage devices. The EU is looking to stop the sales of internal combustion engine vehicles by 2035 and phase all internal combustion vehicles by 2050, implying that light-duty vehicles will be powered by hydrogen, electricity or biofuel [101]. In 2050, the prediction shows 60 % of the total vehicle fleets will be EVs. Considering this, having EVs as energy storage devices would be remarkable. By comparing EV as ESS, we estimate the total ESS replaced by EV through V2G. This study considers PHS as a secondary ESS. The secondary storage represents all the storage available in Spain. It is not necessary to increase the capacity of PHS in order to meet the secondary capacity requirement of an ESS from this study; there can be another storage system installed in its



(a) Influence of V2G acceptance and BA on system performance

(b) Influence of V2G acceptance rate and battery availability on EV energy flow and number of charging cycles in an EV.

Note: BA – battery availability; For 0% V2G acceptance, the EV energy flow and charging cycle for V2G is zero.

Fig. 14. Sensitivity analysis on V2G acceptance and battery availability.

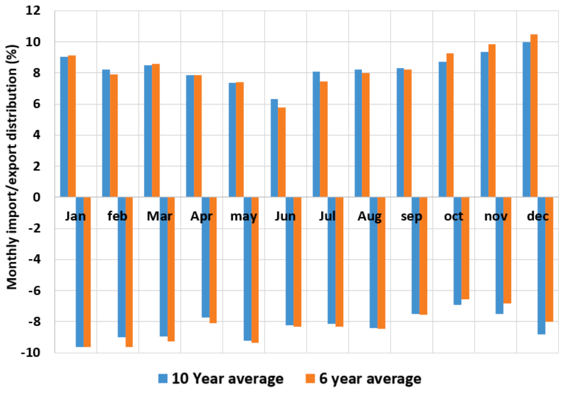


Fig. A1. Monthly import/export distribution

place.

As in section 3.2.2, this analysis also serves the two main purposes,

1. To identify the amount of ESS required if EV is not employed.
2. Analyse how changes in EV numbers influence the total energy flow and system performance.

We identify 235 GW of PV and 328 GW of wind as the best combination to have zero energy shortage with 50 TWh import and 17 TWh export. Starting from 0 EVs participating in V2G to 28.7 million EVs (which is the total light-duty vehicles in 2021) and the model identifies the secondary energy storage required to meet zero energy shortage in each case. To identify the influence of EV volume on results, we perform a sensitivity analysis on EV volume ranging from 0 EVs to 28.7 million EVs in the 2050 scenario as well. Fig. 13a shows the simulation results from the analysis of EV number and secondary ESS requirement and Fig. 13b shows the simulation results of the impact of change in EV volume on hourly reliability and self-sufficiency.

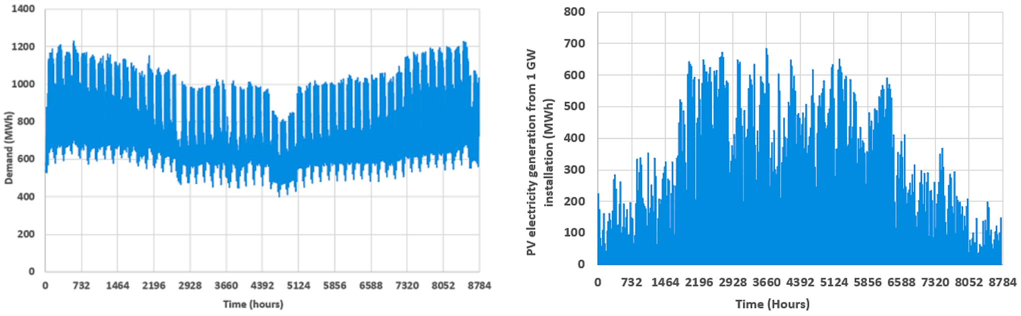
Fig. 13a shows the importance of EVs as an energy storage system and ESS demand if EVs are not used for energy storage purposes. Focusing on the 2050 scenario with 60 % of the total light-duty vehicles as EVs and 5535 MW PHS installation, the excess energy generation is 204 TWh. If the number of EVs participating in V2G decreases, the storage through V2G decreases and to maintain the same self-sufficiency, hourly reliability and energy shortage point, the system needs more secondary ESS systems. If no EV participates in V2G, the approximate requirement of ESS is 2750 GW of new storage units. If EVs replace fossil cars, at a slower pace, e.g.: 40 % of EVs (11.5 million EVs) out of all light-duty vehicles in 2050, to have a 100 % self-sufficiency system which provides 97 % of energy from RES, the system needs 1077 GW of new storage units. Further having more EVs, i.e., 50 % and 60 % reduces the requirement of the new storage system to 540 GW and 30 GW respectively.

Fig. 13b shows the impact of the change in EV volume in the 2050 scenario with no new addition to secondary ESS. When EV growth is slower than anticipated, with 11.48 million EVs (40 % EVs) in 2050, without any new energy storage units in the system, self-sufficiency decreases. From Fig. 13b, we can observe that the self-sufficiency decreases to 98.6 % with an hourly reliability of 99 %. With no EV connected to the grid through V2G, the system reliability reduces to 93 % with hourly reliability of 94 %.

3.3.3. *Sensitivity analysis on V2G acceptance and battery availability*

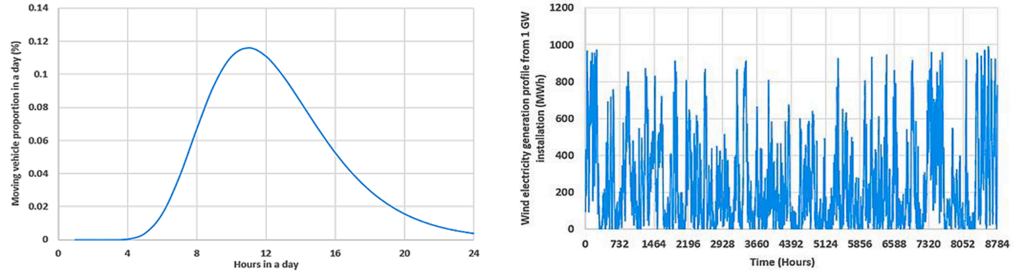
As explained in section 3.2.3, V2G technology provides attractive energy storage possibilities, using the batteries of electric vehicles. However, the balancing potential of V2G technology is dependent on several factors such as V2G acceptance rate and range anxiety [96–100]. In this analysis, we investigate the effects of these two prime variables on V2G's energy storage and flow capacity in the initial results.

In the initial simulation, we assume 10 % V2G acceptance with 80 % battery availability, with a maximum SOC of 100 % and minimum SOC of 10 %. In this analysis, we simulated different V2G acceptance rates, from 0 to 100 %, and battery capacity ranging from 20 % to 80 % reserved for V2G purposes. For the simulation, we consider 235 GW of PV and 328 GW of wind energy installation with 17.22 million EVs (60 % of total light-duty vehicles) connected to the grid through a 22-kW bi-directional charger. Fig. 14 shows the results of the simulation. Fig. 14a shows the simulation results on the influence of V2G acceptance and battery availability on system performance and Fig. 14b shows the influence of V2G acceptance and battery availability on EV energy flow and charging cycles per year. Since the change in self-sufficiency is small, the self-sufficiency of the plot starts from 94 % and on a different



a: Electricity demand in 1 year

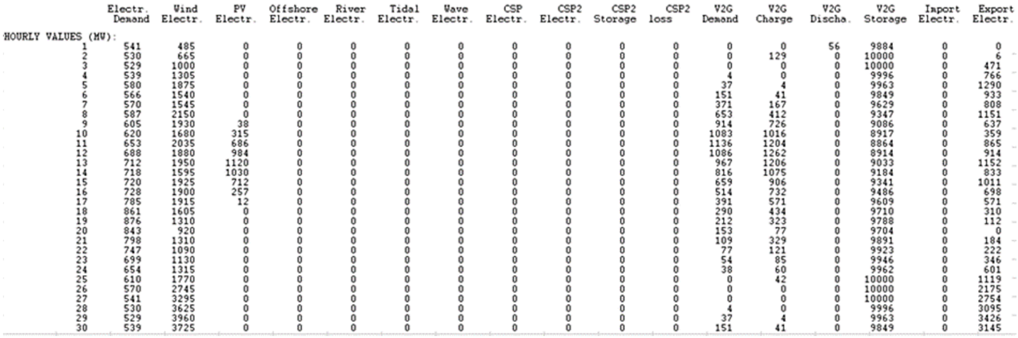
b: PV generation profile over a year



c: EV moving profile in a day

d: Wind generation profile over a year

Fig. A2. Inputs for model validation



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                      Electr.     Wind       PV Offshore    River    Tidal     Wave      CSP     CSP2     CSP2     CSP2      V2G      V2G      V2G      V2G   Import   Export
                       Demand   Electr.  Electr.  Electr.  Electr.  Electr.  Electr.  Electr.  Electr.  Storage  loss      Demand   Charge  Discha.  Storage  Electr.  Electr.
HOURLY VALUES (MW):
                   1      541      485        0        0        0        0        0        0        0        0        0        0        0       56     9884        0        0
                   2      530      665        0        0        0        0        0        0        0        0        0        0      129        0    10000        0        6
                   3      529     1000        0        0        0        0        0        0        0        0        0        0        0        0    10000        0      471
                   4      539     1305        0        0        0        0        0        0        0        0        0        4        0        0     9996        0      766
                   5      580     1875        0        0        0        0        0        0        0        0        0       37        4        0     9963        0     1290
                   6      566     1540        0        0        0        0        0        0        0        0        0      151       41        0     9849        0      933
                   7      570     1545        0        0        0        0        0        0        0        0        0      371      167        0     9629        0      808
                   8      587     2150        0        0        0        0        0        0        0        0        0      653      412        0     9347        0     1151
                   9      605     1930       38        0        0        0        0        0        0        0        0      914      726        0     9086        0      637
                  10      620     1680      315        0        0        0        0        0        0        0        0     1083     1016        0     8917        0      359
                  11      653     2035      686        0        0        0        0        0        0        0        0     1136     1204        0     8864        0      865
                  12      688     1880      984        0        0        0        0        0        0        0        0     1086     1262        0     8914        0      914
                  13      712     1950     1120        0        0        0        0        0        0        0        0      967     1206        0     9033        0     1152
                  14      718     1595     1030        0        0        0        0        0        0        0        0      816     1075        0     9184        0      833
                  15      720     1925      712        0        0        0        0        0        0        0        0      659      906        0     9341        0     1011
                  16      728     1900      257        0        0        0        0        0        0        0        0      514      732        0     9486        0      698
                  17      785     1915       12        0        0        0        0        0        0        0        0      391      571        0     9609        0      571
                  18      861     1605        0        0        0        0        0        0        0        0        0      290      434        0     9710        0      310
                  19      876     1310        0        0        0        0        0        0        0        0        0      212      323        0     9788        0      112
                  20      843      920        0        0        0        0        0        0        0        0        0      153       77        0     9704        0        0
                  21      798     1310        0        0        0        0        0        0        0        0        0      109      329        0     9891        0      184
                  22      747     1090        0        0        0        0        0        0        0        0        0       77      121        0     9923        0      222
                  23      699     1130        0        0        0        0        0        0        0        0        0       54       85        0     9946        0      346
                  24      654     1315        0        0        0        0        0        0        0        0        0       38       60        0     9962        0      601
                  25      610     1770        0        0        0        0        0        0        0        0        0        0       42        0    10000        0     1119
                  26      570     2745        0        0        0        0        0        0        0        0        0        0        0        0    10000        0     2175
                  27      541     3295        0        0        0        0        0        0        0        0        0        0        0        0    10000        0     2754
                  28      530     3625        0        0        0        0        0        0        0        0        0        4        0        0     9996        0     3095
                  29      529     3960        0        0        0        0        0        0        0        0        0       37        4        0     9963        0     3426
                  30      539     3725        0        0        0        0        0        0        0        0        0      151       41        0     9849        0     3145
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Fig. A3. Detailed simulation result from Energyplan.

scale (on the Y axis).

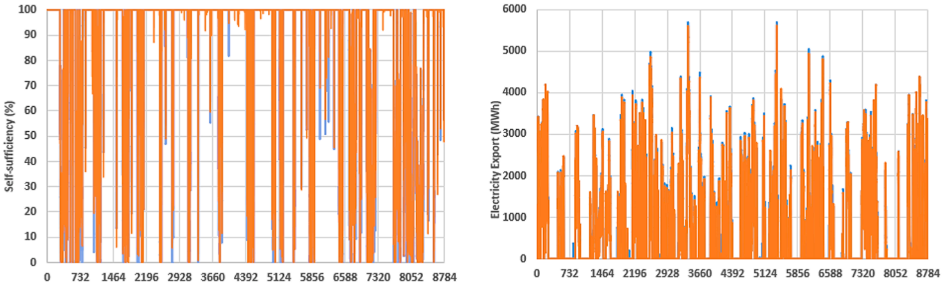
From Fig. 14a, we can observe that the self-sufficiency of the RE system is declining as the V2G acceptance rate and battery availability drop, the same as the results in section 3.2.3. With a lower V2G acceptance rate, fewer EVs are connected to the grid for energy transfer and the total ESS capacity available through V2G decreases. This will reduce the energy storage and retrieval potential. This leads to excess energy generation during peak production periods and energy shortage during peak demand periods, as shown in Fig. 14a. This reduces the self-sufficiency and the hourly reliability of the system. While for the same V2G acceptance rate, a decrease in available battery capacity for V2G service also reduces the storage capacity through V2G service. This will result in the reduction of self-sufficiency and hourly reliability of the system.

Fig. 14b shows the change in energy flow through EVs and the number of charging cycles dedicated for V2G purposes for different operational scenarios. From the results, we can observe that an EV has to go through more charging cycles with lower V2G acceptance rates. In addition to this, lower V2G acceptance reduces the maximum possible storage/extraction, and hence the energy flow. Considering the battery availability, the lower battery capacity dedicated to V2G has to go through fewer charging cycles for lower V2G acceptance scenarios. For the 10 % V2G acceptance scenario, EVs have to go through only 60 charging cycles/year for 20 % battery availability compared to 160 cycles EV has to go through per year for an 80 % battery availability scenario. It is because an EV with a higher battery dedicated facilitates more energy flow, which leads to more charging/discharging cycles, while with lower battery dedicated to V2G only facilitates small energy flow with a small battery capacity for storage. With a V2G acceptance rate, a low V2G acceptance rate puts more pressure on each vehicle. With 10 % V2G acceptance and 50 % battery availability, each EV has to go through 116 full charging cycles as compared to 73 and 54 charging cycles with 30 % and 50 % V2G acceptance.

From the results, we can observe that with 50 % V2G acceptance and 50 % battery availability, we lose approximately 1 % self-sufficiency (hourly reliability – 99.4) as compared to the scenario with 100 % V2G acceptance and 80 % battery availability (hourly reliability – 99.9). The results also show a 30 % V2G acceptance rate with 50 % battery availability helps to achieve 99.1 % hourly reliability with 98.6 % system self-sufficiency. Subsequently, the study indicates that V2G services using EV batteries substantially can reduce RES intermittency issues, also if less than half of the owners are willing to be part of the V2G service.

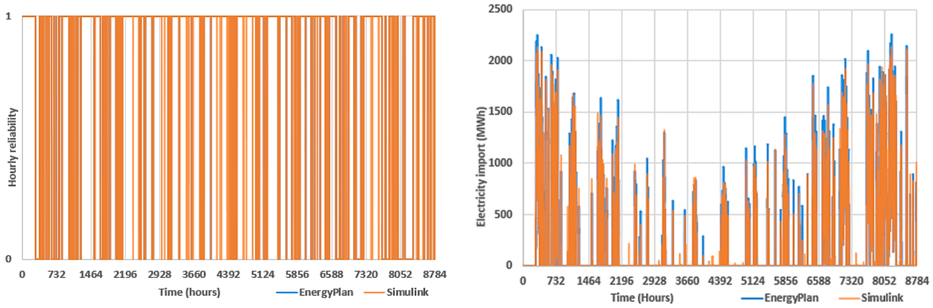
4. Discussion

Renewable energy systems are crucial in order to mitigate the challenges of climate change. To support sustainable development in Spain,



a: Self-sufficiency each hour over the simulation period

b: Electricity export each hour over the simulation period



c: Hourly reliability each hour over the simulation period

d: Electricity import each hour over the simulation period

Fig. A4. Simulation results from both models.

the Spanish government introduced future energy goals. Building sustainable energy solutions is not only about deploying wind turbines and solar panels; it is about transforming our energy infrastructure at its core by reimagining how we generate, store, and distribute power. To support a sustainable future with RES, it is essential to have an energy storage system as well to overcome the intermittency. In this study, we examine the possibility of using EV batteries to store energy through V2G technology.

The study results presented in sections 3.2 and 3.3 show that V2G can positively support Spain in achieving its energy goals by using EV batteries to store energy without the need for new ESS. The results from sections 3.2.1 and 3.3.1 show that 100 % energy generation within the country demands more RES installations. With all energy generation in-house, the RES needs to meet the energy demands at all times, which is not practical due to the intermittent nature of RES, even with the energy storage option. There would be a time when ESS does have not sufficient energy to meet the peak demands. The results show that even for RE supported grid, it is vital to have an external source (such as a reserve power plant or energy import from the neighbouring country) to support the peak demand periods. The results showed that energy trade helps to reduce the total RES installation needed to cover internal energy demand. In the 2030 scenario, with 18 TWh energy import, the model estimates a requirement of 120 GW of PV and 100 GW of wind energy in combination with 3.15 million EVs to meet the 42 % share in the annual energy mix. Comparing with the latest update on the estimates, which is to have 214 GW of total installed capacity by 2030. This includes 160 GW from renewable generation and 22 GW from various forms of storage [102].

The plan for 2030 includes the new installation of hydropower and combined gas power plants with carbon capture, which is not included in the model. Instead, the model considers PV and wind to replace such installations. With the energy storage system, the plan is to include 22 GW of new storage system. With V2G technology, 22 GW storage can be achieved through 220,000 EVs, with a 100-kWh battery considering 100 % V2G acceptance and battery availability. With immense investments in sustainable solutions and rapid deployments of new technologies, governmental policy can encourage V2G. However, 100 % V2G acceptance and battery availability from the community is impossible, as these are the main obstacles in V2G [96,98,103]. A more realistic scenario will be in 2030 with 50 kWh battery capacity, 50 % V2G acceptance and 50 % battery dedicated for V2G purposes, 1.76 million EVs can provide 22 GW energy storage. Further going down with 40 % V2G acceptance and 40 % battery dedicated for V2G, 2.75 million EVs still can provide 22 GW energy storage. Focusing on the electrifying transportation sector with EVs, it is wise to use them to their full potential to reduce the carbon footprint from new installations. In addition to this, V2G offers higher rated output contrary to normal ESS. To facilitate V2G, it is essential to connect EVs to their chargers when not in operation. Connecting one million EVs to the grid through a 7 kW directional charger gives a rated power of 7 GW. From 22 GW storage with a service duration of 8 h only gives a rated output of 2.75 GW.

The results from sections 3.2.2 and 3.3.2 show the impact of EV as ESS. The results show that V2G facilitates a large capacity of virtual energy storage system (based on V2G acceptance and battery availability ratio). For the 2030 scenario, the analysis focuses on 3.15 million EVs with 100 % V2G acceptance and 80 % battery availability. This provides a total capacity of 252 GWh storage potential. To replace this storage potential provided by the EV fleet, 122 GW installation of secondary ESS is required. For the 2050 scenario, the model estimates that the EV provide a total storage capacity of 1.4 TW and 2.7 TW of secondary ESS is required to replace the storage capacity provided by the EV. Even though 100 % V2G acceptance and 80 % battery availability seem optimistic, the results also show in such conditions, the total charging cycles the vehicle has to go through is 85 cycles in the 2030 scenario and 44 cycles in the 2050 scenario. Considering the former assumption for V2G acceptance and battery dedicated for a duration of 10 years, under the 2030 scenario, the vehicle has to go through a total of 850 cycles under the 2030 scenario and 440 cycles under the 2050 scenario, both of which are less than the total number of cycles a battery has to go through to reach the end of life (2000 cycles) However, reducing V2G acceptance and battery availability put more pressure on the vehicles participating on V2G technology and the number of cycles per year increases, as shown in the result in the section 3.2.3 and 3.3.3. Furthermore, the study by Thingvad et al [104] shows a battery degradation of 10 % and 17.8 % for a period of 2 years and 5 years with a 23 kWh battery delivering primary frequency regulation for 15 h per day with a daily energy throughput of 50.6 kWh respectively. Analysing different battery charging strategies for EVs by Bui et al [105], the study reports a battery degradation of 0.0165 % with V2G against 0.0140 % for a week of EV usage. The additional degradation of 0.0025 %/week of capacity fade is experienced by the battery due to V2G technology, which is 17 % higher than normal battery degradation. Nevertheless, very little research has been done on the practical implementation of V2G technology, it is essential for battery degradation analysis to explicitly confirm the battery degradation under the V2G process and to perform an economic analysis to identify the incentives that have to be offered to the EV users to participate in V2G technology. With proper changes in policies to support V2G along with proper research on V2G effects on battery and financial incentives, it may be possible to have higher V2G acceptance and batteries dedicated to V2G in the real world.

Despite uncertainties about the viability of using EVs as ESS in the future, advanced research in the automobile sector supports the wide-scale implementation of V2G technology in the future. The introduction of autonomous vehicles plays a pivotal role, as cutting-edge automobiles incorporate onboard intelligent control systems that can actively monitor V2G interactions and battery functionalities. This seamless integration ensures optimal performance and efficient energy utilization. Moreover, ongoing advancements in wireless charging technologies and centralized control mechanisms for charging and discharging further contribute to the establishment of sophisticated smart V2G systems, minimizing the need for extensive human intervention. The research and development in these areas are supporting an intelligent energy grid that can leverage virtual ESS.

Nevertheless, we also acknowledge the potential challenges associated with V2G technology, such as a lower acceptance rate, insufficient infrastructure; particularly the scarcity of charging stations, and the influence of V2G on power grid energy dynamics. The European Union (EU) is committed to achieving zero pollution from cars in 2040. Consequently, there are plans to modernize the grid system and transition the entire infrastructure to accommodate electric transportation systems. It is anticipated that sufficient charging stations will be implemented to cater to the growing number of EVs. To enhance the acceptance rate, it is required to make policy adjustments favouring V2G and motivating EV owners to participate in V2G. Furthermore, Mehdizadeh et al [106] and Parson et al [107] report high V2G participation with monetary compensations which shows offering adequate V2G compensation can also motivate EV owners to participate in V2G technology.

With more EVs participating in V2G, it could influence the power grid energy dynamics considerably. An uncontrolled charging process can create voltage and frequency disturbances in the grid system. Uncontrolled charging can lead to voltage unbalances in weak low-voltage grids, which can become a major power quality issue [108]. Some of the previous studies show that proper charging and discharging of EVs can control the problems caused to an extent [109–112]. The studies report that careful planning of charging station placements, setting up systems to initiate car charging at delayed times and employing smart control systems can overcome the issues of grid issues from the uncontrolled charging process [109–113]. While utilizing vehicle-to-grid (V2G) technology presents challenges with a controlled charging process. However, advanced, and smart control systems can overcome these challenges. Through the centralised control system, the frequency and voltage drop, or rise can be monitored and the rate of charging and discharging of EVs can be controlled. The maximum charging and discharging rate will be controlled by the charger power and advanced control algorithms will effectively control the operation with the least impact on the grid stability.

Furthermore, this conceptual study includes a few assumptions which are realistic and simplified in the timeframe under consideration within the model's context. All these assumptions can be grouped as i) simplified technical assumptions and ii) technically realistic. Simplified technical assumptions represent realistic system behaviour of systems that are too complex for modelling. These simplified assumptions aim to make modelling these complex systems manageable and computationally less demanding, while sufficiently approaching realistic system functioning. The simplified technical assumptions consist of

- Fixed annual output in the hydropower system
- Considering the whole EV fleet as one big battery pack.
  - Considering the electricity grid as a single grid system.
  - Considering the 1:1 EV and charger ratio

Modelling of Hydropower systems to replicate real-world operation needs to estimate the average head, water availability in reservoir and turbine power. It is possible to model that for a single power plant. Doing for a whole country makes it difficult. In addition to this, it is also essential to address the water inflow in these reservoirs. As we cannot predict the inflow precisely, capturing the physical characteristics is complex. However, it is possible to co-simulate with another simulation software to estimate the energy generation from hydropower. Nonetheless, relying on historical hydro energy production data from previous years helps mitigate the impact of this simplified assumption. The second simplified technical assumption is considering the whole EV fleet as a big battery pack and not considering individual driving patterns for reasons of the practicality of the mode development. Considering larger fleets with millions of EVs with unique driving profiles requires millions of data points and computational power to process the data each hour. This requires no less than a supercomputer to simulate a period of 1 year, which is challenging. To avoid this, in future studies, we plan to cluster drivers with similar profiles and identify multiple such clusters for simulation to reduce the need for high computational time and result in more refined findings. The third simplified technical assumption of the electricity grid is represented in a simplified manner as a single system. In reality, the electricity generation and electricity consumption points vary in the grid, which requires multilevel modelling of electricity systems. Since V2G technology is more emphasized in this study, a detailed grid and computationally intensive grid model with high resolution is not needed. In future studies, we plan to consider multiple energy generation and consumption nodes instead of a single nationwide grid system. Finally, acknowledging the last assumption, which assumes one charger for each EV (1:1 ratio) parked while connected to the grid. Although this ratio seems high compared to current charge point availability, proper planning of infrastructure could pave the way for more efficient and scalable charging solutions in the future. Development in the field of wireless charging will also simplify the connectivity challenge. The impact of lower charger-EV ratios is also explored in this study by modelling different V2G acceptance rates, which can also be interpreted as reflecting different availability rates of bidirectional chargers. In addition to this, the model includes some technically realistic assumptions such as:

- the connection of EVs to the grid when they are not moving.
- 100 kWh battery capacity for EV
- 7 kW charger in the 2030 scenario and 22 kW charger in 2050 scenario

Technically realistic assumptions represent the system, which is not available at present, but will be available in the near future, i.e., 2030 and 2050. Connecting EVs to chargers while not using them is not practical now. However, several studies have shown that, in the future, with the Internet of Things, automated vehicles and wireless DC chargers, EVs could be connected to chargers and grid when they are not in use without any human involvement, which facilitates a controlled charging process to maintain the grid frequency and stability [114–116]. The second realistic assumption concerns the battery capacity of EVs. For the simulations, 100 kWh battery capacity is considered. Currently, the battery pack for EVs ranges from 40 kWh – to 120 kWh, with only a handful of EVs having battery capacity above 100 kWh. Since we have seen a big change in EV battery capacities, the probability of reaching the assumed capacity is very high. Furthermore,

more than 60 % or more of EV users now have a 7-kW uni-directional charger. So, the probability of having a 7-kW bi-directional charger is very high if the EV user has enough motivation to participate in V2G. To increase the user's willingness to participate, it is essential to update the governmental policy to support V2G technology. V2G is a part of Spain's proposal for 2030 and 2050 goals. Assuming positive changes in policy favouring V2G policies, having a 7-kW bidirectional charger in 2030 and a 22-kW charger in 2050 is realistic.

The overall results show that there is a high potential in Spain for V2G to support reaching energy targets by contributing to grid balancing. The analysis shows EV numbers have a considerable influence on energy flow; the same influence is expected with battery availability for V2G. Even though this case study focuses on Spain, the results will be similar to other countries with similar solar irradiance and wind profiles. However, changing the geographical location may lead to different outcomes in results because of the varying nature of weather, usage profile and RES generation profiles. To improve the understanding of the supported grid, future studies will analyse and compare more variables and countries from different latitudes and longitudes to identify the impact of V2G technology under different operating conditions.

5. Conclusion

This conceptual study identifies the potential of V2G technology to use the batteries of EVs as a virtual ESS. Giving more attention to V2G services as compared to ESS, this study analyses how large-scale integration of RES can benefit from V2G as an energy storage technology. Analysing the 2030 and 2050 energy goals of Spain, this research article shows the required RES installation to meet the demand, energy exchange possibilities and impacts along with the influence of V2G technology of a RE-supported grid.

To conduct the study, we develop a model in the Simulink platform in MATLAB, and we validated it through a model comparison with the Energyplan software. The model carries out the 2030 and 2050 scenario analysis in 3 sections, which include analysis of RES installation and excess energy generation (without external support or import, with external support and with energy import), analysis of the influence of EV as primary ESS and sensitivity analysis on EV volume and finally a sensitivity analysis of V2G acceptance and battery availability for V2G process.

The results show that having EV batteries as virtual ESS through V2G technology would be a potential and sustainable option. To fulfil the energy goals of Spain in 2030, to have 42 % of the total energy from RES, the model estimates a requirement of 800 GW RES installations, without any external support or energy imports. Considering the energy import of 18 TWh, this installation goes down to a total RES requirement of 220 GW (120 GW PV and 100 GW wind energy) with 3.15 million EVs for energy storage purposes. The 18 TWh import (less than 2 % of annual demand) helps to meet the energy demand during peak periods and reduces the RES installations by 70 %. The analysis of the 2050 scenario also shows results in a similar pattern. To have 97 % of Spain's energy from RES, the model estimates a total RES requirement of 1300 GW without any external support for energy import. With an import of 50 TWh (5 % of annual demand), this required RES installation goes down to less than 600 GW (235 GW PV and 328 GW of wind energy) with 22.7 million EVs. The results from the analysis of the influence of EVs as primary ESS and sensitivity analysis on EV volume show that 3.15 million EVs provide a huge storage capacity in 2030 and 122 GW installation of secondary ESS is required to swap EVs to support the grid. In 2050, EVs will provide a total storage capacity of 1.4 TW with 22.7 million EVs, and 2.7 TW of secondary ESS is required to replace the storage capacity provided by the EV. This result shows the potential of V2G technology to interconnect stand-alone EVs into a virtual ESS. Furthermore, the studies on V2G acceptance and battery availability show that higher battery availability and V2G acceptance led to more energy flow through EVs and reduced charging cycles. When V2G acceptance or battery availability goes down, it affects the total storage capacity negatively reduces energy flow and puts more effort into the battery through more charging/discharging cycles. Nevertheless, this study does not discuss further battery degradation, policy analysis and economic analysis which is essential to identify the solutions to improve the V2G acceptance rate. Further study is essential to determine the battery degradation and economic aspects of V2G technology.

Appendix 3 shows the simulation results of the initial 30 h from the Energyplan model. Observing hour 10, the electricity demand is 620 MW, while electricity generation from wind and PV is 1680 MW and 315 MW, respectively. Having an excess electricity generation of 1375 MW, the EV demand during that hour is 1083 MW. Because of 11 % EV move during the hour, the model only uses 1016 MW of excess electricity for EVs (with 90 % charger efficiency, the energy reached by EV is 914 MW) and the rest of the excess electricity is used for export purposes. Only satisfying 914 MW out of the 1083 MW requirement, the rest of the electricity for travelling (169 MW) is taken from the EV batteries, reducing the available electricity in the storage from 9086 MW to 8917 MW. The Simulink model also captures this dynamic nature of simulation.

CRediT authorship contribution statement

Shemin Sagaria: Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Mart van der Kam:** Conceptualization, Visualization, Writing – review & editing. **Tobias Boström:** Writing – review & editing, Visualization, Supervision, Methodology, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix

Monthly average energy exchange between 2012 to 2022

Fig. A1

Inputs for model validation

Fig. A2

Simulation results from Energyplan Software

Fig. A3

Appendix 3 shows the simulation results of the initial 30 hours from the Energyplan model. Observing hour 10, the electricity demand is 620 MW, while electricity generation from wind and PV is 1680 MW and 315 MW, respectively. Having an excess electricity generation of 1375 MW, the EV demand during that hour is 1083 MW. Because of 11% EV move during the hour, the model only uses 1016 MW of excess electricity for EVs (with 90% charger efficiency, the energy reached by EV is 914 MW) and the rest of the excess electricity is used for export purposes. Only satisfying 914 MW out of the 1083 MW requirement, the rest of the electricity for travelling (169 MW) is taken from the EV batteries, reducing the available electricity in the storage from 9086 MW to 8917 MW. The Simulink model also captures this dynamic nature of simulation.

Comparison of simulation results from the developed model and Energyplan software

Fig. A4

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